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INTERGOVERNMENTAL PANEL ON climate change

Chapter 7

Wind Power

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Length

Chapter 7 has been allocated a maximum of 68 (with a mean of 51) pages in the SRREN. The actual chapter length (excluding references & cover page) is 72 pages: a total of 4 pages over the maximum (21 over the mean, respectively).

Expert reviewers are kindly asked to indicate where the Chapter could be shortened by 4-21 pages in terms of text and/or figures and tables to reach the mean length.

References

References highlighted in yellow are either missing or unclear.

Chapter 7: Wind energy

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EXECUTIVE SUMMARY

Wind energy offers significant potential for near- and long-term carbon emissions reduction. The wind energy capacity installed at the end of 2008 delivered roughly 1.5% of worldwide electricity supply, and that contribution could grow to in excess of 20% by 2050. Though wind speeds vary regionally, all continents have areas with substantial resource potential. On-shore wind is a mature technology that is already being deployed at a rapid pace in many countries. In good wind resource regimes, the cost of on-shore wind can be competitive with other forms of electricity generation, and no fundamental technical barriers exist that preclude increased levels of wind penetration into electricity supply systems. Continued technology advancements in on- and off-shore wind are expected, further improving wind energy's carbon emissions mitigation potential.

The wind energy market has expanded rapidly. Modern utility-scale wind turbines have evolved from small, simple machines to large-scale, highly sophisticated devices, driven in part by more than three decades of basic and applied research and development. The resulting cost reductions, along with government policies to expand renewable energy supply, have led to rapid market development. Cumulative installed wind capacity increased from just 10 GW in 1998 to more than 120 GW at the end of 2008, and wind energy was a significant contributor to the electricity capacity additions of Europe and the United States during the latter years of this period. Most additions have been on-shore, but several European countries are embarking on ambitious programmes of off-shore wind deployment. Total investment in wind installations in 2008 equaled roughly US$45 billion, while direct employment totaled 400,000. Despite these developments, global wind energy capacity at the end of 2008 supplied a modest fraction of worldwide electricity demand, and growth has been concentrated in Europe, the U.S., and segments of Asia; the top five countries by cumulative installed capacity at the end of 2008 were the U.S., Germany, Spain, China, and India. Policy frameworks continue to play a significant role in the expansion of wind energy utilization, and further growth – especially off-shore and in under-represented regions – is likely to require additional policy measures.

The scale of the global wind resource is sizable. On a worldwide basis, studies have consistently found that the technically-exploitable wind energy resource (on- and off-shore) exceeds global electricity demand. Though the wind energy resource is not fixed (but instead reflects the status of the technology, among other factors) and further advancements in wind resource assessment methods are needed, the resource itself is unlikely to constrain further global wind development. Sufficient wind resource potential also exists in most regions of the world to enable significant additional wind development. That said, the resource is not evenly distributed across the globe, and wind energy will not contribute equally in meeting the needs of every region. Additionally, the wind energy resource is not uniformly located near population centres – some of the resource is therefore economically inaccessible given the costs of new transmission infrastructure. Research into the effects of global climate change on the geography and variability of the wind resource is nascent; however, research to date suggest that it is unlikely that these changes will greatly impact the global potential for wind energy to reduce carbon emissions.

Analysis and experience demonstrate that successful integration of wind energy is achievable. Wind energy has characteristics that pose new challenges to electricity system planners and operators, such as variable electrical output, reduced predictability, and locational dependence. Nonetheless, wind electricity has been successfully integrated into existing electricity networks without compromising system security and reliability; in some countries, wind energy supplies in excess of 10% of aggregate annual electricity demand, while instantaneous wind energy deliveries have exceeded 45% of demand. Because the characteristics of the existing electricity system determine the ease of integrating wind energy, acceptable penetration limits and the operational costs of integration are system-specific. Nevertheless, theoretical analyses and practical experience suggest that at low to medium penetration levels the operational integration of wind energy poses no fundamental economic or technical challenges. As wind energy increases, network integration issues must be addressed both at the local and network levels through system stability and balancing requirements. Active management through a broad range of strategies is anticipated, including the use of flexible generation resources (natural gas, hydropower), wind energy forecasting and output curtailment, and increased coordination and interconnection between power systems; increased demand management and electrical storage technologies may also be used. Finally, significant new transmission infrastructure, both on-shore and off-shore, would be required to access the most robust wind resource areas.

Environmental and social issues will affect wind energy deployment opportunities. Wind energy has significant potential to reduce GHG emissions, together with the emissions of other air pollutants, by displacing fossil fuel-based electricity generation. The energy used, and emissions produced, in the manufacture and installation of wind turbines is small compared to the energy generated and emissions avoided over the lifetime of the turbines. In addition, the variability of wind energy production does not significantly affect the carbon emissions benefits of increased reliance on wind energy. Alongside these benefits, however, the development of wind energy can have detrimental effects to the environment and people [TSU: humans]. Modern wind technology involves large structures up to 100 metres high, so wind turbines are unavoidably visible in the landscape, and planning wind energy facilities often arouses local public concern. Appropriate siting of wind turbines is important in minimizing the impact of noise, flicker, and electromagnetic interference, and engaging local residents in consultation during the planning stage is an integral aspect of project development. Moreover, the environmental impacts of wind energy extend beyond direct human interests, as the construction and operation of both on- and off-shore wind projects can directly impact wildlife (e.g., bird and bat collisions) and indirectly impact ecosystems. Attempts to measure the relative impacts of power generation suggest that wind energy has a low environmental footprint compared to other electricity generation options, but local impacts do exist, and techniques for assessing, minimizing, and mitigating those concerns could be improved. Moreover, while public acceptance and scientific concerns should be addressed, streamlined planning and siting procedures for both on-shore and off-shore wind may be required to enable more-rapid growth.

Technology innovation and underpinning research can further reduce the cost of wind [TSU: energy]. Current wind turbine technology has been developed for on-shore applications, and has converged to three-bladed upwind rotors, with variable speed operation. Though on-shore wind technology is reasonably mature, continued incremental advancements are expected to yield improved design procedures, increased reliability and energy capture, reduced operation and maintenance [TSU: (O&M)] costs, and longer turbine life. In addition, as off-shore wind energy gains more attention, new technology challenges arise, and more-radical technology innovations are possible (e.g., floating turbines, two-bladed downwind rotors). Advancements can also be gained through more-fundamental research to better understand the operating environment in which wind turbines must operate. It is estimated that continued research and development, testing, and operational experience could yield reductions in the levelized cost of on-shore wind energy of 7.5-25% by 2020, and 15-35% by 2050. The available literature suggests that off-shore wind energy applications have greater potential for cost reductions: 10-30% by 2020 and 20-45% by 2050.

Wind energy offers significant potential for near- and long-term carbon emissions reduction. Given the maturity and cost of on-shore wind technology, increased utilization of wind energy offers the potential for significant near-term carbon emissions reductions: this potential is not conditioned on technology breakthroughs, and related systems integration challenges are manageable. As technology advancements continue, especially for off-shore wind technology, greater contributions to carbon emissions reduction are possible in the longer term. Based on a review of the carbon and energy scenarios literature, wind energy's contribution to global electricity supply could rise from 1.5% at the end of 2008 to 20% or greater by 2050 if ambitious efforts are made to reduce carbon emissions. Achieving this level of global wind energy utilization would likely require not only economic incentive policies of adequate size and stability, but also an expansion of wind energy utilization regionally, increased reliance on off-shore wind energy, technical and institutional solutions to transmission constraints and operational integration concerns, and proactive efforts to mitigate and manage social and environmental concerns associated with wind energy deployment.

7.1 Introduction

This chapter addresses the potential role of wind energy in reducing global and regional GHG emissions. Wind energy (in many applications) is a mature renewable energy (RE) source that has been successfully deployed in many countries, is technically and economically capable of significant continued expansion, and its further exploitation may be a crucial aspect of global GHG reduction strategies. Though wind speeds vary considerably by location, all continents have substantial regions with a technically viable and economically exploitable resource.

Wind energy relies, indirectly, on the energy of the sun. Roughly two percent of the solar radiation received by the earth is converted into kinetic energy (Hubbert, 1971), the main cause of which is the imbalance between the net outgoing radiation at high latitudes and the net incoming radiation at low latitudes. Global equilibrium is maintained, in part, through wind currents, with the earth's rotation, geographic features, and temperature gradients greatly affecting the location and nature of those winds (Burton *et al.*, 2001). The use of wind energy requires that the kinetic energy of moving air be converted to useful energy. Because the theoretically-extractable kinetic energy in the wind is proportional to the cube of wind speed, the economics of using wind for electricity generation are highly sensitive to local wind conditions.

Wind energy has been used for millennia (for historical overviews of the use of wind energy, see, e.g., Gipe, 1995; Ackermann and Soder, 2002; Pasqualetti *et al.*, 2004). Sailing vessels relied on the wind from at least 3,100 BC, with mechanical applications of wind energy in grinding grain, pumping water, and powering factory machinery following, first with vertical axis devices and subsequently with horizontal axis turbines. By 200 B.C., for example, simple windmills in China were pumping water, while vertical-axis windmills were grinding grain in Persia and the Middle East. By the 11th century, windmills were used in food production in the Middle East; returning merchants and crusaders carried this idea back to Europe. The Dutch refined the windmill and adapted it for draining lakes and marshes in the Rhine River Delta. When settlers took this technology to the New World in the late 19th century, they began using windmills to pump water for farms and ranches. Industrialization and rural electrification, first in Europe and later in America, led to a gradual decline in the use of windmills for mechanical applications. The first successful experiments with the use of wind to produce electricity are often credited to Charles Brush (1887) and Paul La Cour (1891). Use of wind electricity in rural areas and, experimentally, in utility-scale applications, continued throughout the mid-1900s. However, the use of wind to generate electricity on a commercial scale began in earnest only in the 1970s, first in Denmark on a relatively small scale, then on a much larger scale in California (1980s), and then in Europe more broadly (1990s).

The primary use of wind energy of relevance to climate change mitigation is to produce electricity from larger, utility-scale wind turbine generators, deployed either in a great number of smaller wind energy projects or a smaller number of much larger projects. Such turbines typically stand on tubular towers of 60-100 [TSU: all towers?] meters in height, with three-bladed rotors that are often 70-100 meters in diameter; larger machines are under development. Such projects are commonly sited on land: as of 2009, wind projects sited in shallow and deeper water off-shore are a relatively small proportion of global wind energy installations. As wind energy deployment expands and as the technology becomes more mature, off-shore wind is expected to become a more significant source of overall wind energy supply.

Due to their potential importance to climate change mitigation, this chapter emphasizes these larger on- and off-shore wind electricity applications. Notwithstanding this focus, wind energy has served and will continue to meet other energy service needs. In remote areas of the world that lack centrally provided electricity supplies, smaller wind turbines can be deployed alone or alongside other technologies to meet individual household or community electricity demands; small turbines of this nature also serve marine energy needs. Small-island or remote electricity grids can also employ wind energy, along with other energy sources, to meet local needs. Even in urban settings that already have ready access to electricity, smaller wind turbines can, with careful siting, be used to meet a portion of building energy needs. New concepts for high-altitude wind energy machines are also under consideration, and in addition to electricity generation wind will continue to meet mechanical energy and propulsion needs in specific applications. Though not the focus of this chapter, these additional wind energy applications and technologies are briefly summarized in Text Box 7.1.

Drawing on available literature, this chapter begins by describing the size of the global wind energy resource, the regional distribution of that resource, and the possible impacts of climate change on the wind resource (Section 7.2). The chapter then reviews the status of and trends in modern utility-scale wind technology, both on-shore and off-shore (Section 7.3). The chapter then turns to a discussion of the status of the wind energy market and industry developments, both globally and regionally, and the impact of policies on those developments (Section 7.4). Near-term issues associated with the integration of variable wind into electricity networks are addressed (Section 7.5), as is available evidence on the environmental and social impacts of wind energy development (Section 7.6). The prospects for further technology improvement and innovation are summarized (Section 7.7), and historical, current, and potential future cost trends are reviewed (Section 7.8). The chapter concludes with an examination of the potential future deployment of wind energy, focusing on the carbon mitigation and energy scenarios literature (Section 7.8).

Text box 7.1. Other wind energy applications and technologies.

Beyond the use of large, modern wind turbines for electricity generation, a number of additional wind energy applications and technologies are currently employed or are under consideration. Though these technologies and applications are at different phases of market development, and each holds a certain level of promise for scaled deployment, none are likely to compete with traditional large on- and off-shore wind technology from the perspective of carbon emissions reduction, at least in the near- to medium-term.

Small wind turbines for electricity generation. Smaller-scale wind turbines can be and are used in a wide range of applications. Though wind turbines from hundreds of watts to tens of kilowatts in size do not benefit from the economies of scale that have helped reduce the cost of utility-scale wind energy, they can sometimes be economically competitive with other supply alternatives in areas that do not have access to centrally provided electricity supply (Byrne *et al.*, 2007). For rural electrification or isolated areas, small wind turbines can be used on a stand-alone basis for battery charging or can be combined with other supply options (e.g., solar and/or diesel) in hybrid systems (EWEA, 2009). As an example, China had 57 MW of cumulative small (<100 kW) wind capacity installed at the end of 2008 (Li and Ma, 2009). Small wind turbines can also be employed in grid-connected applications in both rural and urban settings, and for both residential and commercial electricity customers (the use of medium-sized turbines of perhaps 500 kW to 1 MW is also promising for utility-scale applications in certain developing countries where road infrastructure and manufacturing capacity may limit the production and transport of larger turbines). Though the use of wind energy in these applications can provide economic and social development benefits, the current and future size of this market makes it an unlikely source of significant long-term carbon emissions reductions; AWEA (2009b) estimates global installations of <100 kW wind turbines from leading manufacturers at under 40 MW in 2008. In addition, for urban settings where the wind resource can be quite poor, the carbon emissions associated with the manufacture and installation of small wind turbines may not be repaid in the form of zero-carbon electricity generation (Carbon Trust, 2008b).

Wind energy to meet mechanical and propulsion needs. Among the first technologies to harness the energy from the wind are those that directly used the kinetic energy of the wind as a means of marine propulsion, grinding of grain, and water pumping. Though these technologies were first developed long ago, there remain opportunities for the expanded use of wind energy to meet mechanical and propulsion needs (e.g., Purohit, 2007). New concepts to harness the energy of the wind for propulsion are also under development, such as using large kites to complement diesel engines for marine transport; demonstration projects on mid-sized vessels and studies have found that these systems may yield fuel savings of 10-50%, depending on the technology and wind conditions (O'Rourke, 2006; Naaijen and Koster, 2007; Aschenbeck *et al.*, 2009).

High-altitude wind electricity. High-altitude wind energy systems have recently received some attention as an alternative approach to generating electricity from the wind (Argotov and Silvennonein, 2007; Canale *et al.*, 2007; Roberts *et al.*, 2007; Archer and Caldeira, 2009; Argotov *et al.*, 2009). The principal motivation for the development of this technology is the sizable resource of high-speed winds present in jet streams. There are two main approaches to high-altitude wind energy that have been proposed: (1) tethered wind turbines that are maintained at altitudes up to 10,000 meters and transmit electricity to earth via cables, and (2) base stations that convert the kinetic energy from the wind collected via kites at altitudes of about 1,000 meters to electricity at ground level. Though some research has been conducted on these technologies and on the size of the potential resource, the technology remains in its infancy, and scientific and institutional challenges must be overcome before a realistic estimate of the carbon emissions reduction potential of high-altitude wind can be developed.

7.2 Resource potential

The global exploitable wind resource is not fixed, but is instead related to the status of the technology, the economics of wind energy, and other constraints to wind energy development. Nonetheless, a growing number of global wind resource assessments have demonstrated that the world's technically exploitable wind energy resource exceeds global electricity demand, and that ample potential exists in most regions of the world to enable significant wind development. However, the wind resource is not evenly distributed across the globe, and wind energy will therefore not contribute equally in meeting the needs of every region. This section summarizes available evidence on the size of the global wind energy resource (7.2.1), the regional distribution of that resource (7.2.2), and the possible impacts of climate change on wind energy resources (7.2.3). This section focuses on long-term average annual resource potential; for a discussed [TSU: discussion] of seasonal and diurnal patterns, as well as shorter-term wind output variability, see Section 7.5.

7.2.1 Global technical resource potential

A number of studies have been conducted to estimate the technically-exploitable global wind energy resource. In general, two methods can be used to make these estimates: first, an observation-based method can construct a surface wind distribution by interpolating available wind speed measurements; and second, numerical weather prediction models can be applied to an area of interest. The studies that have investigated the global wind resource use varying combinations of these two approaches, have sometimes focused on only on-shore wind energy applications, and have typically used relatively simple analytical techniques with coarse spatial and temporal resolution.[1] Additionally, it is important to recognize that any estimate of the potential wind resource is not a single, fixed quantity – it will change as wind technology develops and as more is learned about technical, environmental, and social concerns that may influence development.

Despite these caveats, the growing numbers of global wind resource assessments have demonstrated that the world's technically exploitable wind energy resource exceeds total global electricity supply. Synthesizing the available literature, the IPCC's Fourth Assessment Report identified 600 EJ/yr of available on-shore wind energy resource potential (IPCC, 2007), just 0.95 EJ (0.2%) of which was being used for wind energy applications in 2005. The IPCC (2007) estimate appears to derive, originally, from a study authored by Grubb and Meyer (1993). Using the standard IEA method of deriving primary energy equivalence (where electricity supply, in TWh, is translated directly to primary energy, in EJ), the IPCC (2007) estimate of on-shore wind energy potential is 180 EJ/yr (50,000 TWh/yr), almost three times greater than global electricity demand in 2007 (19,800 TWh).[2]

Since the Grubb and Meyer (1993) study, a number of additional analyses have been conducted to estimate the global technical potential for wind energy (Table 7.1).

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[1] Wind project developers may rely upon global and regional wind resource estimates to obtain a general sense for the locations of potentially promising development prospects. However, on-site collection of actual wind speed data at or near turbine hub heights remains essential for most wind energy projects of significant scale.

[2] The IPCC (2007) cites Johansson *et al.* (2004), which obtains its data from UNDP (2000), which in turn references WEC (1994) and Grubb and Meyer (1993). To convert from TWh to EJ, the documents cited by IPCC (2007) use the standard conversion, and then divide by 0.3 (i.e.., the "substitution" method of energy accounting in which renewable electricity supply is assumed to substitute the primary energy of fossil fuel inputs into conventional power plants, accounting for plant conversion efficiencies). The IEA's primary energy accounting method does not take this last step, and instead counts the electricity itself as primary energy (that is, it translates TWh of electricity supply directly into EJ), so this chapter reports the IPCC (2007) figure at 180 EJ/yr, or roughly 50,000 TWh/yr. This figure is close to that estimated by Grubb and Meyer (1993).

Table 7.1. Global assessments of technical wind resource potential.

Study	**Scope**	**Methods and Assumptions***	**Results****
Lu *et al.* (2009)	On-shore & Off-shore	>20% capacity factor (Class 1); 100m hub height; 9 MW/km^2; based on coarse simulated model dataset; exclusions for urban and developed areas, forests, inland water, permanent snow/ice; off-shore assumes 100m hub height, 6 MW/km^2, <92.6 km from shore, <200m depth, no other exclusions	Theoretical/Technical: 840,000 TWh 3,050 EJ
Hoogwijk and Graus (2008)	On-shore & Off-shore	Updated Hoogwijk *et al.* (2004) by incorporating off-shore wind, assuming 100m hub height for on-shore, and altering cost assumptions; for off-shore wind, study updates and adds to earlier analysis by Fellows (2000); other assumptions as listed below under Hoogwijk *et al.* (2004); technical potential defined here in economic terms: <$0.18/kWh (2005$) for on-shore wind and <$0.09/kWh (2005$) for off-shore wind in 2050	Technical/Economic: 110,000 TWh 400 EJ
Archer and Jacobson (2005)	On-shore & Near-Shore	>Class 3; 80m hub height; 9 MW/km^2 spacing; 48% average capacity factor; based on wind speeds from surface stations and balloon-launch monitoring stations; technical potential = 20% of theoretical potential	Theoretical: 627,000 TWh 2,260 EJ Technical: 125,000 TWh 450 EJ
WBGU (2004)	On-shore & Off-shore	Multi-MW turbines; based on interpolation of wind speeds from meteorological towers; exclusions for urban areas, forest areas, wetlands, nature reserves, glaciers, and sand dunes; local exclusions accounted for through corrections related to population density; off-shore to 40m depth, with sea ice and minimum distance to shore considered regionally; sustainable potential = 14% of technical potential	Technical: 278,000 TWh 1,000 EJ Sustainable 39,000 TWh 140 EJ
Hoogwijk *et al.* (2004)	On-shore	>4 m/s at 10m (some less than Class 2); 69m hub height; 4 MW/km^2; assumptions for availability and array efficiency; based on interpolation of wind speeds from meteorological towers; exclusions for elevations >2000m, urban areas, nature reserves, certain forests; reductions in use for many other land-use categories; economic potential defined here as <$0.10/kWh (2005$)	Technical: 96,000 TWh 350 EJ Economic: 53,000 TWh 190 EJ
Fellows (2000)	On-shore & Off-shore	50m hub height; 6 MW/km^2 spacing; based on upper-air model dataset; exclusions for urban areas, forest areas, nature areas, water bodies, and steep slopes; additional maximum density criterion; off-shore assumes 60m hub height, 8 MW/km^2 spacing, to 40m depth, 5-40 km from shore, with 75% exclusion; technical potential defined here in economic terms: <$0.23/kWh (2005$) in 2020; focus on four regions, with extrapolations to others; some countries omitted altogether	Technical/Economic: 46,000 TWh 170 EJ
WEC (1994)	On-shore	>Class 3; 8 MW/km^2 spacing; 23% average capacity factor; based on an early global wind resource map;	Theoretical: 484,000 TWh

		technical potential = 4% of theoretical potential	1,740 EJ Technical: 19,400 TWh 70 EJ
Grubb and Meyer (1993)	On-shore	>Class 3; 50m hub height; assumptions for conversion efficiency and turbine spacing; based on an early global wind resource map; exclusions for cities, forests, and unreachable mountain areas, as well as for social, environmental, and land use constraints, differentiated by region (results in technical potential = ~10% of theoretical potential, globally)	Theoretical: 498,000 TWh 1,800 EJ Technical: 53,000 TWh 190 EJ

* Where used, wind resource classes refer to the following wind densities at a 50 meter hub height: Class 1 (< 200 W/m^2), Class 2 (200-300 W/m^2), Class 3 (300-400 W/m^2), Class 4 (400-500 W/m^2), Class 5 (500-600 W/m^2), Class 6 (600-800 W/m^2), and Class 7 (>800 W/m^2).

** Converting between EJ and TWh is based on the primary energy method of accounting used by IEA. Definitions for theoretical, technical, economic, and sustainable potential are provided in the glossary of terms, though individual authors cited in Table 7.1 often use different definitions of these terms.

Among these studies, the global technical potential for wind ranges from a low of 70 EJ/yr to a high of 1,000 EJ/yr, or from 19,400 to 278,000 TWh/yr (excluded here is Lu *et al*., 2009, as that study estimates potential wind generation that is arguably somewhere in between technical and theoretical potential); this range equates to one to 15 times 2007 global electricity demand. Results vary based on whether off-shore wind is included, the wind speed data that are used, the areas assumed available for wind development, the rated output of wind turbines installed per unit of land area, and the assumed performance of wind projects, which itself is related to hub height and turbine technology.

There are three main reasons to believe that many of the studies reported in Table 7.1 may understate the technically exploitable global wind resource. First, several of the studies are dated, and advances in wind technology and resource assessment methods have occurred since that time. The five most-recent studies listed in Table 7.1, for example, calculate larger technical resource potentials than the earlier studies (i.e., Hoogwijk *et al.,* 2004; WBGU, 2004; Archer and Jacobson, 2005; Hoogwijk and Graus, 2008; Lu *et al*., 2009).

Second, a number of the studies included in Table 7.1 exclude off-shore wind energy. The scale of the off-shore wind energy resource is, at least theoretically, enormous, and constraints are less-technical [TSU: less technical] than they are economic. In particular, water depth, accessibility, and grid interconnection may constrain development to relatively near-shore locations in the medium term, though technology improvements are expected, over time, to enable deeper-water and more-remote installations (EWEA, 2009). Relatively few studies have investigated the global off-shore technical wind resource potential, and neither Archer and Jacobson (2005) nor WBGU (2004) report off-shore potential separately from the total potential reported in Table 7.1. In one study of global potential, Leutz *et al*. (2001) estimate an off-shore wind potential of 37,000 TWh/yr at depths less than 50m. Building from Fellows (2000), Hoogwijk and Graus (2008) estimate a global off-shore wind potential of 6,100 TWh/yr by 2050 at costs under $0.09/kWh in real 2005$ (Fellows, 2000, provides an estimate of almost 5,000 TWh/yr). In another study, Siegfriedsen *et al*. (2003) calculate the technical potential of off-shore wind outside of Europe as 4,600 TWh/yr. Lu *et al*. (2009) estimate an off-shore wind resource potential of 150,000 TWh/yr, 42,000 TWh/yr of which is available at depths of less than 20m, though this number represents theoretical – not technical – potential. Regionally, studies have estimated the scale of the off-shore wind resource in the E.U.

(Matthies *et al*., 1995; Delft University *et al*., 2001), the U.S. (Kempton *et al*., 2007; Jiang *et al*., 2008; Heimiller *et al*., 2010), and China[3]. In general, these studies have found that the scale of the off-shore wind resource is significant, and highly dependent on assumed technology developments.

Finally, even some of the more-recent studies reported in Table 7.1 likely understate the global wind energy resource due to methodological limitations. The global assessments described here often use relatively simple analytical techniques with coarse spatial resolutions, rely on interpolations of wind speed data from a limited number (and quality) of surface stations, and apply limited validation from wind speed measurements in prime wind resource areas. Enabled in part by an increase in computing power, more sophisticated and finer-resolution atmospheric modelling approaches are beginning to be applied (and, increasingly, validated) on a country or regional basis, as described in more depth in Section 7.2.2. Experience shows that these increasingly sophisticated techniques have often identified greater actual wind resource potential than the earlier global assessments had previously estimated, especially in areas that previously were found to have limited resource potential (see Section 7.2.2). These approaches have only begun to be applied on a global basis, and the results of these analyses are likely to lead to revisions to global estimates of technical wind resource potential, and to an improved understanding of the location of that potential. As visual demonstration of some of these advancements, Figure 7.1(a,b) presents two global wind resource maps, one created in 1981 (Elliott *et al*., 1981) and another in 2009 (3TIER, 2009).

(a) 1981 Global wind resource map

(Elliott *et al*., 1981)

(b) 2009 Global wind resource map

(3TIER, 2009)

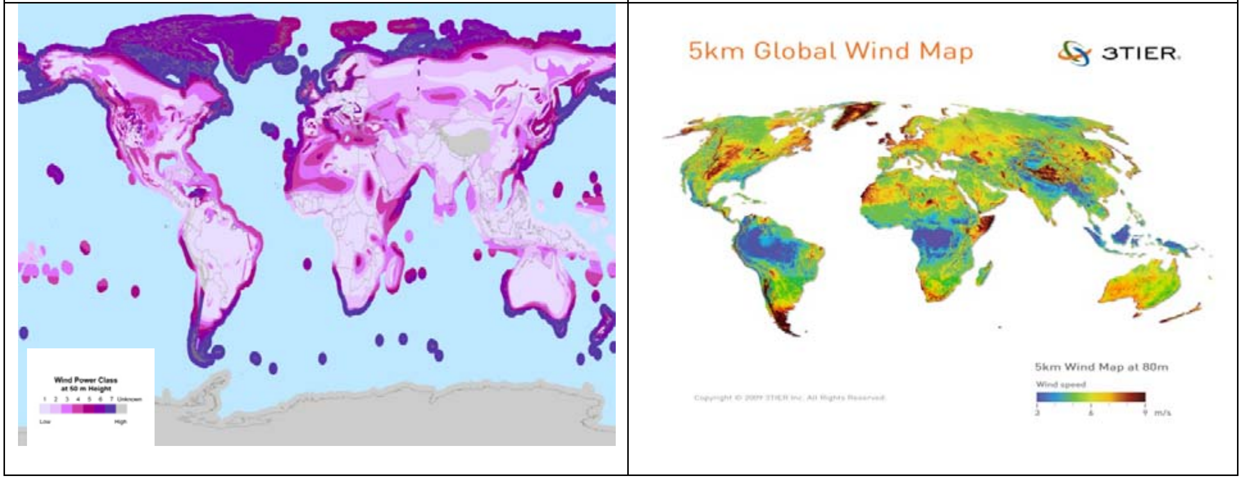

Figure 7.1(a,b). Example global wind resource maps from 1981 and 2009.

Despite these limitations, the current body of literature does support one main conclusion: the global wind resource is unlikely to be a limiting factor on global wind development. Instead, economic constraints associated with the cost of wind energy, the institutional constraints and costs associated with transmission grid access and operational integration, and issues associated with social acceptance and environmental impacts are likely to restrict growth well before the absolute technical limits to harvesting the wind resource are met.

7.2.2 Regional technical resource potential

7.2.2.1 Global assessment results, by region

The global wind resource assessments summarized is Section 7.2.1 generally find that not only is the wind resource unlikely to pose a significant *global* barrier to wind energy expansion, but also

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[3] http://swera.unep.net/

that ample technical potential exists in most regions of the world to enable significant wind development. That said, the wind resource is not evenly distributed across the globe, and wind energy will therefore not contribute equally in meeting the energy needs and GHG reduction demands of every region.

The global assessments presented earlier have come to varying conclusions about the relative on-shore wind resource potential of different regions, and Table 7.2 summarizes results from a sub-set of the assessments. These differences are due to variations in wind speed data and key input parameters, including the minimum wind speed assumed to be exploitable, land-use constraints, density of wind development, and assumed wind project performance (Hoogwijk *et al.*, 2004); differing regional categories also complicate comparisons. Nonetheless, the wind resource in North America and the former Soviet Union are found to be particularly sizable, while some areas of Asia appear to have relatively limited on-shore resource potential. Visual inspection of Figure 7.1 also demonstrates limited resource potential in certain areas of Latin America and Africa, though other portions of those continents have significant potential. Caution is required in interpreting these results, however, as other studies find significantly different regional allocations of global potential (e.g., Fellows, 2000), and more detailed country and regional wind resource assessments have come to differing conclusions on, for example, the wind resource in East Asia and other regions (Hoogwijk and Graus, 2008)**.**

Table 7.2. Regional allocation of global technical on-shore wind resource potential*.

Grubb and Meyer (1993)		**WEC (1994)**		**Hoogwijk and Graus (2008)****		**Lu et al. (2009)**	
Region	%	Region	%	Region	%	Region	%
Western Europe	9%	Western Europe	7%	OECD Europe	4%	OECD Europe	4%
North America	26%	North America	26%	North America	41%	North America	22%
Latin America	10%	L. America & Carib.	11%	Latin America	11%	Latin America	9%
E. Europe & FSU	20%	E. Europe & FSU	23%	Non-OECD Europe & FSU	18%	Non-OECD Europe & FSU	26%
Africa	20%	Sub-Saharan Africa	7%	Africa and Middle East	9%	Africa and Middle East	17%
Australia	6%	M. East & N. Africa	9%	Oceania	15%	Oceania	13%
Rest of Asia	9%	Pacific	14%	Rest of Asia	3%	Rest of Asia	9%
		Rest of Asia	4%				

* Some regions have been combined to improve comparability among the four studies.

** Hoogwijk et al. (2004) show similar results.

Hoogwijk *et al.* (2004) also compare on-shore [TSU: emphasis helpful] technical potential against regional electricity consumption in 1996. In most of the 17 regions evaluated, on-shore wind potential exceeded electricity consumption in 1996. The multiple is over five in 10 regions: East Africa, Oceania, Canada, North Africa, South America, Former Soviet Union, Central America, West Africa, United States, and the Middle East. Areas in which on-shore wind resource potential was estimated to be less than a 2x multiple of 1996 electricity consumption were South Asia (1.9), Western Europe (1.6), East Asia (1.1), South Africa (1), Eastern Europe (1), South East Asia (0.1), and Japan (0.1), though again, caution is warranted in interpreting these results.

The estimates reported in Table 7.2 ignore off-shore [TSU: emphasis helpful] wind potential. Hoogwijk and Graus (2008) estimate that of the 6,100 TWh of technically/economically exploitable off-shore wind resource by 2050, the largest opportunities exist in OECD Europe (approximately

22% of global potential), Latin America (approximately 22%), non-OECD Europe and FSU (approximately 17%), with somewhat less but still significant potential in Asia and Oceania (approximately 13%, each), North America (approximately 9%), and Africa and the Middle East (approximately 4%).

With some exceptions, virtually every region or continent appears to have adequate technically exploitable wind resource potential to enable significant wind energy development. As a result, economic, institutional, social, and land-use constraints are most likely to restrict the growth of wind energy, at least in the medium term.

7.2.2.2 ´Regional assessment results

The global wind energy assessments described previously have, historically, relied primarily on relatively coarse and imprecise estimates of the wind resource, sometimes relying heavily on measurement stations in urban areas with relatively poor exposure to the wind resources (Elliott, 2002; Elliot *et al*., 2004). The regional results from these global assessments, as presented in Section 7.2.2.1, should therefore be considered uncertain, especially in areas in which wind measurement data is of limited quantity and quality. More-detailed country and regional assessments, on the other hand, have benefited from wind energy specific wind speed data collection, increasingly sophisticated numerical wind resource prediction techniques, enhanced validation of model results, and a dramatic growth in computing power. These advancements have allowed more-recent country and regional resource assessments to capture smaller-scale terrain features and temporal variations in predicted wind speeds, at a variety of possible turbine heights.

Initially, these techniques were applied primarily in the E.U.[4] and the U.S.[5], but there are now publicly available high-resolution wind resource assessments covering a wide range of regions and countries. The United Nations Environment Program's Solar and Wind Energy Resource Assessment (SWERA), for example, provides information about wind energy resources in a large number of its partner countries around the world,[6] while the European Bank for Reconstruction and Development has developed RE assessments in its countries of operation (Black and Veatch, 2003). A number of other publicly available country-level assessments have been produced by the U.S. National Renewable Energy Laboratory,[7] Denmark's Risø DTU[8], and others.[9] Additional details on the status of wind resource assessment in China and Russia are offered in Text Box 7.2.

These more-detailed regional wind resource assessments have generally found the scale of the known wind energy resource to be greater than estimated in previous global or regional assessments. This is due primarily to improved data and analytic techniques, and greater resolution of smaller-scale terrain features, but it is also the result of wind turbine technology developments, e.g., higher hub heights and improved machine efficiencies (see, e.g., Elliott, 2002; Elliot *et al*., 2004). Additional methodological improvements to provide even greater spatial and temporal resolution, and enhanced validation of model results with observational data, are needed, as is an expanded coverage of these assessments to a growing number of countries and regions (see, e.g., IEA, 2008; Schreck *et al*., 2008). These developments will further improve our understanding of

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[4] For the latest publicly available European wind resource map, see http://www.windatlas.dk/Europe/Index.htm. Publicly available assessments for individual E.U. countries are summarized in EWEA (2009).

[5] A large number of publicly available U.S. wind resource maps have been produced at the state level, many of which have subsequently been validated by the National Renewable Energy Laboratory (see http://www.windpoweringamerica.gov/wind_maps.asp).

[6] See http://swera.unep.net/index.php?id=7

[7] See http://www.nrel.gov/wind/international_wind_resources.html

[8] See http://www.windatlas.dk/World/About.html

[9] A number of companies offer wind resource mapping assessments for a fee; those assessments are not included in the table.

wind energy resource potential, and will likely highlight regions with high-quality potential that have not previously been identified.

Text box 7.2. Advancements in wind resource assessment in China and Russia

As demonstration of the growing use of sophisticated wind resource assessment tools outside of the E.U. and U.S., historical and ongoing efforts in China and FSU to better characterize those areas' wind resources are described here. In both cases, the wind resource has been found to be sizable compared to present electricity consumption, and recent analyses offer enhanced understanding of the location of those resources.

China's Meteorological Administration (CMA) completed its first wind resource assessment in the 1970s. In the 1980s, a second wind resource investigation was performed based on data from roughly 900 meteorological stations, and a spatial distribution of the resource was delineated. The CMA estimated the availability of 253 GW of technically exploitable on-shore wind resources (Xue *et al*. 2001). More recently, increased access to meteorological observation data and improved data quality are facilitating a more-detailed assessment. This third assessment is based primarily on data from 2,384 meteorological stations, supplemented with data from other sources (CMA, 2006). Though it is still mainly based on measured wind speeds at 10m, most data cover a period of over 50 years. Figure 7.2.2 shows the results of this investigation, focused on the on-shore wind resource. Based on this work, the CMA now estimates 297 GW of on-shore wind potential; other recent research has estimated a far-greater potential resource (see, e.g., McElroy *et al*., 2009; Li and Ma, 2009). To further improve its estimations, the CMA is also executing several projects that rely on mesoscale atmospheric models for wind resource mapping, and is performing higher-resolution resource assessments in several key wind resource areas in China.

Considerable progress has also been made in understanding the magnitude and distribution of the wind energy resource in Russia (as well as the other CIS countries, and the Baltic countries), based in part on data from approximately 3,600 surface meteorological stations and 150 upper-air stations. A recent assessment by Nikolaev *et al*. (2008) uses these data and meteorological and statistical modeling to estimate the distribution of the wind resource in the region (see Figure 7.2.2). Based on this work, and after making assumptions for characteristics and placement of wind turbines, Nikolaev *et al*. (2008) estimate that the technical potential for wind energy in Russia is more than 14,000 TWh/yr, 15-times that of Russia's electricity consumption in 2006. The more promising regions of Russia for wind energy development are in the Western part of the country, the South Ural area, in Western Siberia, and on the coasts of the seas of the North and Pacific Oceans.

(a) China wind resource map

(CMA, 2006)

(b) Russia, CIS, Baltic wind resource map

(Nikolaev *et al*., 2008)

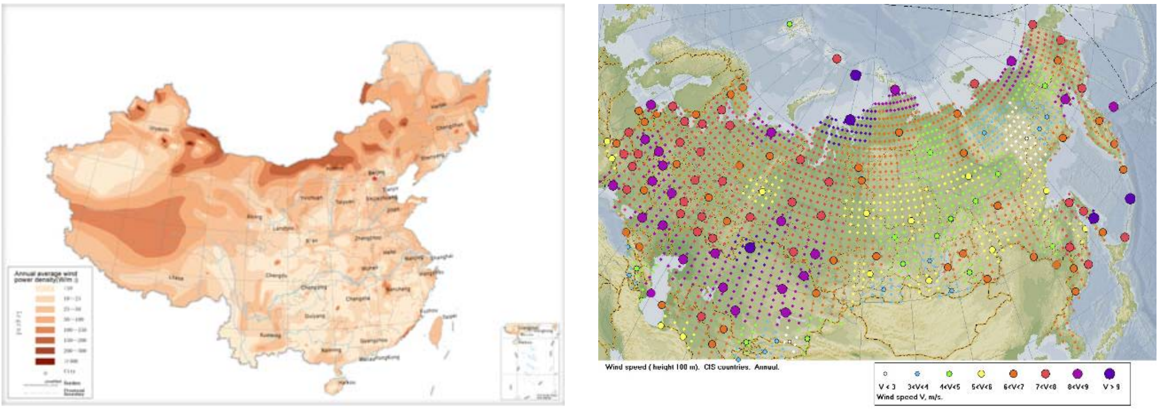


Figure 7.2(a,b). Wind resource maps for China and Russia/CIS/Baltic.

7.2.3 Possible impact of climate change on resource potential

There is increasing recognition that global climate change may alter the geographic distribution and/or the inter- and intra-annual variability of the wind resource, or alter the external conditions for wind developments. However, research in this field is nascent, and Global and Regional Climate Models (GCMs and RCMs) do not fully reproduce contemporary wind climates (Goyette *et al.*, 2003) or historical trends (Pryor *et al.*, 2009). Additionally, empirical and dynamical downscaling studies show large model-to-model variability (Pryor *et al.*, 2005; Pryor *et al.*, 2006). Nevertheless, based on the state-of-the-art, it appears unlikely that mean wind speeds and energy density will change by more than the inter-annual variability (i.e. ±15%) over most of Europe and North America during the present century (Breslow and Sailor, 2002; Pryor *et al.*, 2005; Pryor *et al.*, 2006; Walter *et al.*, 2006; Bloom *et al.*, 2008; Sailor *et al.*, 2008). Brazil has a large wind resource that was estimated to substantially decline by up to 60% by 2100 in one study (Schaeffer *et al.*, 2008), possibly due to the simplifying assumptions employed. Conversely, simulations for the west coast of South America showed increases in mean wind speeds of up to +15% over the same period (Garreaud and Falvey, 2009). Inter-annual variability across much of Europe (the standard deviation of annual wind indices) is ±10-15%, while inter-decadal variability is ±30% (Petersen *et al.*, 1998). Whether this variability has or will change as the global climate evolves is uncertain (Pryor *et al.*, 2009) [TSU: link to previous sentence unclear (South America/Europe)].

The prevalence of extreme winds and the probability of icing have implications for wind turbine design, as well as operation and maintenance [TSU: please use abbr. O&M] (Claussen *et al.*, 2007; Dalili *et al.*, 2009). Preliminary studies from northern and central Europe show some evidence for increased magnitude of wind speed extremes (Pryor *et al.*, 2005; Haugen and Iversen, 2008; Leckebusch *et al.*, 2008), though changes in the occurrence of inherently rare events are difficult to quantify, and further research is warranted. Sea ice, and particularly drifting sea ice, potentially enhances turbine foundation loading for off-shore projects, and changes in sea ice and/or permafrost conditions may also influence access for wind farm maintenance (Laakso *et al.*, 2003). One study conducted in northern Europe found substantial declines in the occurrence of both icing frequency and sea ice extent under reasonable climate change scenarios (Claussen *et al.*, 2007). Other meteorological drivers of turbine loading may also be influenced by climate change but are likely to be secondary in comparison to changes in resource magnitude, weather extremes, and icing issues (Pryor and Barthelmie, 2010).

7.3 Technology and applications

7.3.1 Introduction

Modern utility-scale wind turbines have evolved from small, simple machines to large-scale, highly sophisticated and complicated devices. Scientific and engineering expertise, as well as computational tools and design standards, have developed to support modern wind technology. As a result, wind turbine size has increased by a factor of 100 since the late 1970s and early 1980s, while the cost of energy production from wind has been reduced by a factor of five (EWEA, 2009).

On-shore wind technology can be considered reasonably mature; additional advances in R&D are anticipated, and are expected to further reduce the cost of wind electricity, but current technology is already being manufactured and deployed on a commercial scale. Off-shore wind technology, on the other hand, is still developing, with greater opportunities for additional advancement. This section summarizes the historical development and technology status of utility-scale on-shore and off-shore wind turbines (7.3.2), discusses international wind technology standards (7.3.3), and reviews grid connection issues (7.3.4); a later section (7.7) describes opportunities for further advancements.

7.3.2 Technology development and status

The generation of electricity from wind requires that the kinetic energy of moving air be converted to mechanical and then electrical energy, and the engineering challenge for the wind industry is to design efficient wind turbines to perform this conversion. The amount of energy in the wind available for extraction increases with the cube of wind speed. However, a turbine can capture only a portion of that increase because, when the power in the wind exceeds the wind speed for which the mechanical and electrical system of the machine has been designed (the rated power of the turbine), excess energy is allowed to pass through the rotor uncaptured (see Figure 7.3). Modern utility-scale wind turbines employ rotors that start extracting energy from the wind at speeds of roughly 3-5 m/s. The turbine maximizes power production until it reaches its rated power level, corresponding to a wind speed of approximately 12-15 m/s. At higher wind speeds, control systems limit power output to prevent overloading the wind turbine, either through stall control or through pitching the blades. Turbines will stop producing energy at wind speeds of approximately 25-30 m/s to limit loads on the rotor and prevent damage to the turbine’s structural components.

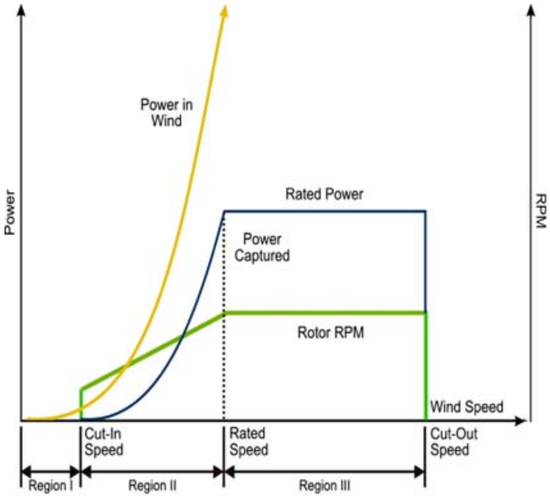


Figure 7.3. Conceptual power curve for modern wind turbine (U.S. DOE, 2008).

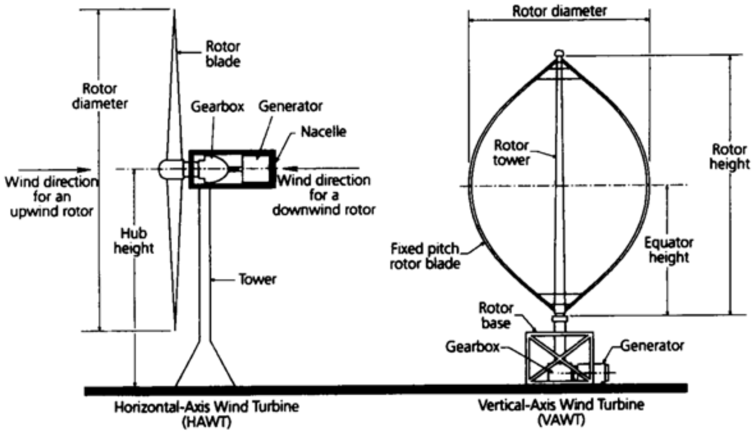
In general, the speed of the wind increases with height above the ground, encouraging wind engineers to design taller and larger wind turbines while minimizing the cost of materials. Wind speeds also vary geographically and temporally, influencing the location of wind projects, the economics of those projects, and the implications of increased wind generation on electric power system operations.

7.3.2.1 On-shore wind technology

In the 1970s and 1980s, a variety of wind turbine configurations were investigated (see Figure 7.4), including both horizontal and vertical axis designs (see Figure 7.5). Gradually, the horizontal axis design came to dominate, although configurations varied, in particular the number of blades and whether those blades were oriented upwind or downwind of the tower. After a period of further consolidation, turbine designs centred (with some notable exceptions) around the 3-blade, upwind rotor; locating the turbine blades upwind of the tower prevents the tower from blocking wind flow onto the turbine (Figure 7.5). The three blades are attached to a rotor, from which power is transferred (sometimes through a gearbox, depending on design) to a generator. The gearbox and generator are contained within a housing called the nacelle.

Source: Risø DTU

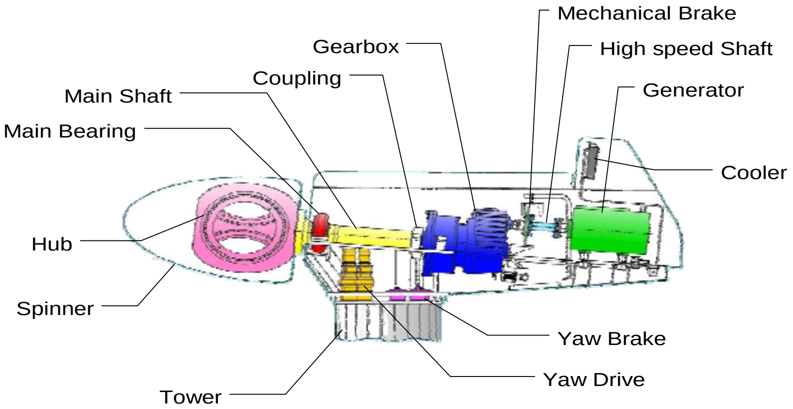
Figure 7.4. Early wind turbine designs.



Source: Risø DTU

Figure 7.5. Horizontal- and vertical-axis wind turbine designs.

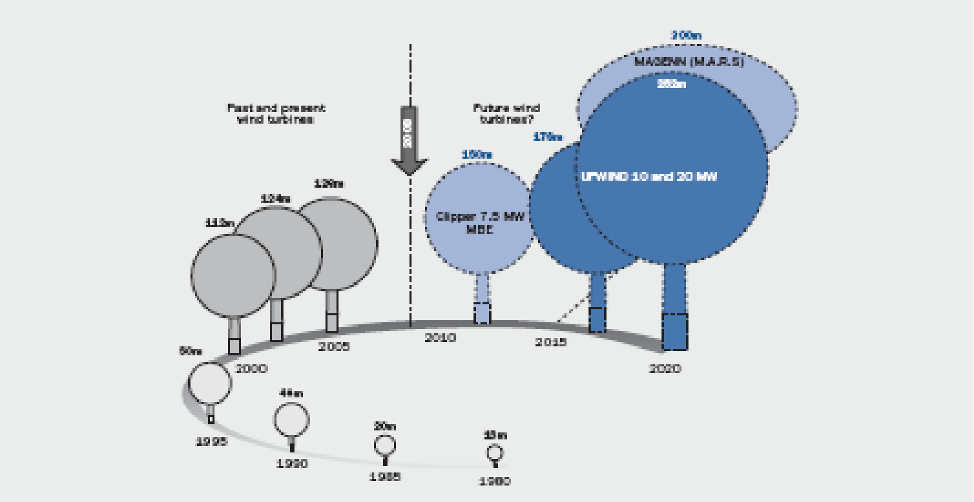
In the 1980s, larger machines were rated at around 100 kW and relied on aerodynamic blade stall to regulate power production from the fixed blades. These turbines generally operated at one or two rotational speeds. As turbine size increased over time, development went from stall control to full-span pitch control in which turbine output is controlled by pitching (i.e., rotating) the blades along their long axis. In addition, the advent of inexpensive power electronics allowed variable speed wind turbine operation. Initially, variable speeds were used to smooth out the torque fluctuations in the drive train caused by wind turbulence, and to allow more efficient operation in variable and gusty winds. More recently, almost all utility system operators require the continued operation of large wind projects during electrical faults, together with being able to provide reactive power: these requirements have accelerated the adoption of variable speed operation with power electronic conversion (see Section 7.5 for a fuller discussion of grid integration issues). Today, wind turbines typically operate at variable speeds using full-span blade pitch control. Blades are commonly constructed from glass polyester or glass epoxy, and the towers are usually tubular steel structures that taper from the base to the nacelle at the top. Figure 7.6 shows the components in a modern wind turbine with a gearbox. In wind turbines without a gearbox, the rotor is mounted directly on the generator shaft.



Source: Vestas

Figure 7.6. The basic components of a modern wind turbine with a gearbox.

Over the past 30 years, average wind turbine capacity ratings have grown significantly (Figure 7.7), with the largest fraction of land-based utility-scale wind turbines installed globally in 2008 having a rated capacity of 1 MW to 3 MW; the average size of turbines installed in 2008 was 1.6 MW (BTM, 2009). Such turbines typically stand on 60-100 meter towers, with rotors 70-100 meters in diameter. The main reason for this continual increase in size has been to try to optimize wind installations by increasing electricity production (taller towers provide access to a higher-quality wind resource, and larger rotors allow a greater exploitation of those winds), reducing installed costs per unit of capacity (installation of a fewer number of larger turbines can, to a point, also reduce installed costs), and reducing maintenance costs (larger turbines can reduce maintenance costs per unit of capacity). For land-based turbines, however, additional growth in turbine size may be limited due to the logistical constraints of transporting the very large blades, tower, and nacelle components by road; the cost of and difficulty in obtaining large cranes to lift the components in place; and the impact of larger turbines on the visual quality of the landscape especially in areas of high population density. As a result, some turbine designers do not expect land-based turbines to grow to a size much larger than about 3-5 MW (U.S. DOE, 2008).



Source: Garrad Hassan

Figure 7.7. Growth in size of commercial wind turbines.

Modern on-shore wind turbines are typically grouped together into wind farms, sometimes called wind projects, which can range from a few megawatts to up to or even exceeding 500 MW. The design requirement for wind turbines is normally 20 years, with 4,000 to 7,000 hours of operation each year depending on the characteristics of the local wind resource. By comparison, a domestic car that travels 20,000 km per year at an average speed of 30 km per hour over a decade operates a total of 6,666 hours.

As a result of the above developments, on-shore wind technology has reached a state of relative maturity such that the industry is considered a viable electricity producing option for power systems. As demonstration of the maturity of the technology [TSU: sentence incomplete?], modern wind turbines have nearly reached the theoretical maximum of aerodynamic efficiency, with the coefficient of performance rising from 0.44 in the 1980s to about 0.50 by the mid 2000s. The value of 0.50 is near the practical limit dictated by the drag of aerofoils and compares with a theoretical limit of 0.59 known as the Betz limit. Moreover, operation and maintenance [TSU: please use abbr. O&M] teams work to maintain high plant availability despite component failure rates that have, in some instances, been higher than expected. Data collected through 2008 show that modern wind turbines in mature markets can achieve an availability of 97% or more (Blanco, 2009; EWEA, 2009; IEA 2009b). Though these results are encouraging, and the technology has reached sufficient commercial maturity to allow large-scale manufacturing and deployment, additional advancements to improve reliability, increase electricity production, and lower costs are anticipated, and are discussed in Section 7.7.

In summary, on-shore wind turbine technology is relatively mature, and is ready for wide-scale deployment. Most of the historical technology developments, however, have occurred in developed countries. Increasingly, developing countries are investigating the potential installation of wind technology. Opportunities for technology transfer in wind turbine design, component manufacturing, and wind project siting exist. In addition, extreme environmental conditions, such as icing or typhoons, may be more prominent in some of these markets, providing impetus for continuing research. Other aspects unique to less developed countries, such as minimal transportation infrastructure, could also influence wind turbine designs as these markets develop.

7.3.2.2 Off-shore wind technology

The first off-shore wind project was built in 1991 at Vindeby, Denmark, and consisted of eleven 450 kW wind turbines. Since then, most off-shore wind installations have taken place in the UK, Denmark, the Netherlands, and Sweden. The off-shore wind sector remains relatively immature and, at the end of 2008, about 1,500 MW of off-shore wind capacity was installed globally, just 1.1% of overall installed wind capacity (BTM, 2009). Interest in off-shore wind is the result of several factors: the higher-quality wind resources located at sea (e.g., higher wind speeds, lower turbulence, and lower shear); the ability to use even-larger wind turbines due to reduced transportation constraints and the potential to thereby gain further economies of scale; the ability for more-flexible turbine designs given the uniqueness of the off-shore environment (e.g., lower turbulence, less wind shear, no constraints on noise); a potential reduction in the need for new, long-distance, land-based transmission infrastructure[10]; the ability to build larger projects than on-shore, gaining project-level economies of scale; and the potential reduction of visual impacts and mitigation of siting controversies if projects are located far-enough from shore (Carbon Trust, 2008a; Snyder and Kaiser, 2009). These factors, combined with a significant off-shore wind resource potential, has created considerable interest in off-shore wind technology in the E.U.; that interest has begun to expand (albeit more slowly) to the U.S., China, and elsewhere.

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[10] Of course, transmission infrastructure would be needed to connect off-shore wind projects with electricity demand centers as well. Whether that infrastructure is more or less extensive than that needed to access on-shore wind varies by location.

Average turbine size for off-shore wind projects is 2-4 MW (as of 2005-2009), with a maximum size of 5 MW, and even larger turbines are under development. Off-shore wind projects installed through 2008 range in size up to roughly 200 MW, with a clear trend towards larger turbines and projects over time. Water depths for off-shore wind turbines installed to date have generally been modest, starting at 5-10 meters and reaching a typical 15-20 meters by 2009, and sea conditions have often been somewhat sheltered. However, as experience is gained, it is expected that water depths will increase and that more exposed locations with higher winds will be utilized.

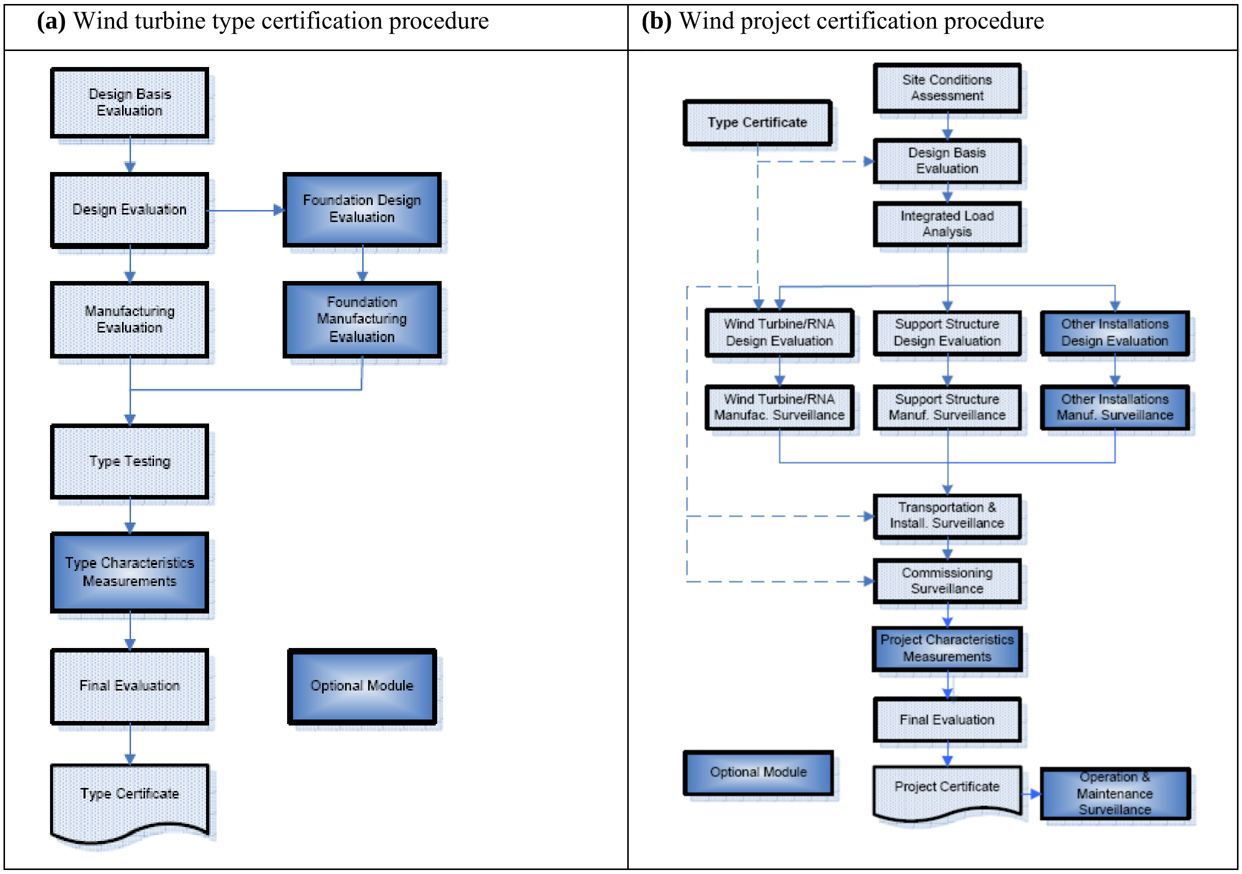
To date, off-shore turbine technology has been very similar to on-shore designs, with some modifications and with special foundations (Musial, 2007; Carbon Trust, 2008a). The mono-pile foundation is the most common, though concrete gravity-based foundations have also been used; a variety of alternative foundation designs are being considered, especially as water depth increases, as discussed in Section 7.7. In addition to differences in foundations, modification to off-shore turbines (relative to on-shore) include structural upgrades to the tower to address wave loading; air conditioned and pressurized nacelles and other controls to prevent the effects of corrosive sea air from degrading turbine equipment; and personnel access platforms to facilitate maintenance. Additional design changes for marine navigational safety (e.g., warning lights, fog signals) and to minimize expensive servicing (e.g., more extensive condition monitoring, on-board service cranes) are common. Wind turbine tip-speed is often greater than for on-shore turbines, in part because concerns about noise are reduced for off-shore projects and higher tip speeds can sometimes lead to greater aerodynamic efficiencies, and tower heights are often lower due to reduced wind shear (i.e., wind speed does not increase with height to the same degree as on-shore).

Off-shore wind technology is still under development, and lower project availabilities and higher operations and maintenance (O&M) [TSU: please use abbr. O&M] costs have been common for the early installations (Carbon Trust, 2008a). Wind technology specifically tailored for off-shore applications will become more prevalent as the off-shore market expands, and it is expected that larger turbines in the 5-10 MW range may come to dominate this market segment (E.U., 2008). More subtle differences in technology are also emerging, due to the different environment in which off-shore turbines operate and the increased need for turbine reliability. For example, the availability of off-shore wind turbines is lower than for on-shore projects due to reduced accessibility resulting from harsh operating conditions; both high winds and seas can make access impossible at times, and jobs that require off-shore cranes can involve considerable delays while waiting for suitably calm conditions. There is therefore a push to design off-shore turbines to reach higher levels of reliability than on-shore turbines (EWEA, 2009).

7.3.3 International wind technology standards

Wind turbines in the 1970s and 1980s were designed using simplified design models, which in some cases led to machine failures and in other cases resulted in design conservatism. The need to address both of these issues, combined with advancements in computer processing power, motivated designers to improve their calculations during the 1990s (Quarton, 1998; Rasmussen *et al.*, 2003). Improved design and testing methods have been codified in International Electrotechnical Commission (IEC) standards, and the rules and procedures for Conformity Testing and Certification of Wind Turbines (IEC, 2008a) relies upon these standards. These certification procedures provide for third-party conformity evaluation of a wind turbine type, a major component type, or one or more wind turbines at a specific location. Certification agencies rely on accredited design and testing bodies to provide traceable documentation of the execution of rules and specifications outlined in the standards in order to certify turbines, components, or projects. The certification system assures that a wind turbine design or wind turbines installed in a given location meet common guidelines relating to safety, reliability, performance, testing. Figure 7.8 (a) illustrates the design and testing procedures required to obtain a wind turbine type certification.

Project certification, shown in Figure 7.8 (b), requires a type certificate for the turbine and includes procedures for evaluating site conditions and turbine design parameters associated with that specific site, as well as other site-specific conditions including soil properties, installation, and project commissioning.


(a) Wind turbine type certification procedure

(b) Wind project certification procedure

Figure 7.8(a,b). Modules for (a) type certification and (b) project certification (IEC, 2008a).

Insurance companies, financing institutions, and project owners normally require some form of certification for projects to proceed. These standards provide a common basis for certification to reduce uncertainty and increase the quality of wind turbine products available in the market. In emerging markets, the lack of highly qualified testing laboratories and certification bodies limits the opportunities for manufacturers to obtain certification according to IEC standards and may lead to lower-quality products. As markets mature and design margins are compressed to reduce costs, reliance on internationally recognized standards will likely become even more widespread to assure consistent performance, safety, and reliability of wind turbines.

7.3.4 Grid connection issues

Wind turbines can affect the reliability of the electrical network. As wind turbine installations have increased, so too has the need for wind projects to become more active participants in maintaining (rather than passively depending on) the operability and power quality of the grid. Focusing here primarily on the technical aspects of grid interconnection, the electrical performance of wind turbines in interaction with the grid is often verified in accordance with IEC 61400-21, in which methods to assess the impact of one or more wind turbines on power quality are specified (IEC, 2008b). Additionally, an increasing number of grid operators have developed minimum requirements (sometimes called “grid codes”) that wind energy facilities (and other power plants) must meet when connecting to the power system (further discussion of these requirements and the institutional elements of wind energy integration are addressed in Section 7.5, and a more general discussion of RE integration is covered in Chapter 8). These requirements can be met through turbine manufacturer modifications to wind turbine designs, or through the addition of auxiliary equipment such as power conditioning equipment.

From a power system reliability perspective, an important part of the wind turbine is the electrical conversion system, which for large grid-connected turbines comes in three broad forms. Fixed-speed induction generators were popular in earlier years for both stall regulated and pitch controlled turbines; in these arrangements, wind turbines were net consumers of reactive power that had to be supplied by the power system. These designs have now been largely replaced with variable speed wind turbines. Two arrangements are common, doubly-fed induction generators (DFIG) and synchronous generators with a full power electronic convertor, both of which are almost always coupled to pitch controlled rotors. These turbines can provide real and reactive-power control and fault ride-through capability, which are increasingly being required for power system reliability. Variable speed machines therefore offer a number of power quality advantages over the earlier turbine designs (Ackermann, 2005). These variable speed designs essentially decouple the rotating masses of the turbine from the electrical power system, a design that offers a number of power quality advantages over the earlier turbine designs (EWEA, 2009). However, this design results in no intrinsic inertial response capability; additional turbine controls must be implemented that create the effect of inertia (Mullane and O'Malley, 2005). Wind turbine manufacturers have recognized this lack of intrinsic inertial response as a long term impediment to wind penetration and are actively pursuing a variety of solutions.

7.4 Global and regional status of market and industry development

The wind energy market has expanded substantially in the 2000s, demonstrating the maturity of the technology and industry, the relative economic competitiveness of wind electricity, and the importance placed on wind energy development by a number of countries through policy support measures. This section summarizes the global (7.4.1) and regional (7.4.2) status of wind energy development, discusses trends in the wind industry (7.4.3), and highlights the importance of policy actions in the wind energy market (7.4.4). Overall, the section demonstrates that the on-shore wind energy technology and industry is already sufficiently mature and cost effective to allow for significant deployment. At the same time, off-shore wind energy is developing slowly, and even on-shore wind expansion has been concentrated in a limited number of regions and contributes just 1.5% of global electricity supply. Further expansion of wind energy, especially off-shore and in under-represented regions, is likely to require additional policy measures.

7.4.1 Global status and trends

Global wind energy capacity has been growing at a rapid pace and, as a result, wind energy has quickly established itself as part of the mainstream electricity industry (see Figure 7.9). From 1998 through 2008, the average annual increase in cumulative installed capacity was 29%. From a cumulative capacity of 10 GW in 1998 the global installed capacity increased twelve-fold in ten years to reach more than 120 GW at the end of 2008, an average annual increase in cumulative capacity of 29%. In another [TSU: wording unclear] record year for new installations, global annual wind capacity additions equalled more than 27 GW in 2008, up from 20 GW in 2007 and 15 GW in 2006 (BTM, 2009; GWEC, 2009). A slower rate of growth in cumulative capacity is expected in 2009, however, in part due to the global economic crisis (BTM, 2009).

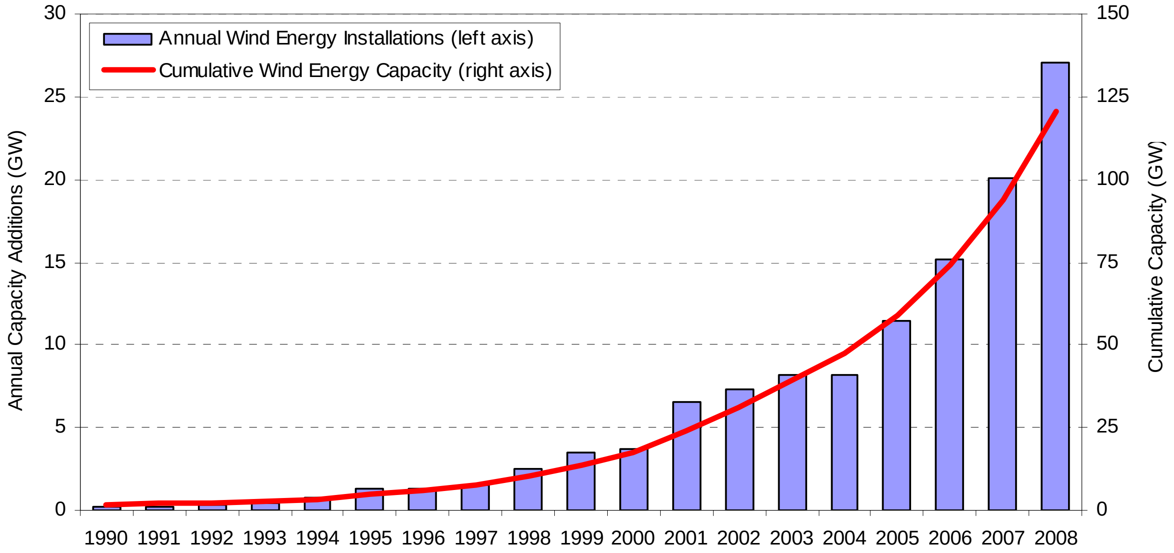


Figure 7.9. Global cumulative and annual installed wind capacity (EWEA, 2009; GWEC, 2009; Wiser and Bolinger, 2009).

The bulk of the capacity has been installed on-shore, with off-shore installations constituting a small proportion of the total wind turbine market. About 1,500 MW of off-shore wind turbines have been installed, primarily in European waters, with plans for a further 4 GW of off-shore wind installation by 2010 (GWEC, 2009). Off-shore wind is expected to develop in a more-significant way in the years ahead as the technology becomes more mature, and as on-shore wind sites become constrained by resource availability and/or siting challenges in some regions (BTM, 2009).

In terms of economic value, the total cost of new wind generating equipment installed in 2008 was US$45 billion (2005$; REN21, 2009). Direct employment in the wind energy sector in 2008 has been estimated to equal roughly 105,000 in the E.U. (Blanco and Rodrigues, 2009) and 85,000 in the United States (AWEA, 2009a). Worldwide, direct employment in the wind industry is estimated at approximately 400,000 (GWEC, 2009).

Despite these trends, wind generated electricity remains a relatively small fraction of worldwide electricity supply. The total wind energy capacity installed by the end of 2008 would, in an average year, deliver roughly 1.5% of worldwide electricity supply, up from 1.2% at the end of 2007 and 0.9% at the end of 2006 (Wiser and Bolinger, 2009).

7.4.2 Regional and national status and trends

The countries with the highest total installed wind energy capacity at the end of 2008 were the United States (25 GW), Germany (24 GW), Spain (17 GW), China (12 GW), and India (10 GW). After its initial start in the United States in the 1980s, wind energy growth centred on countries of the E.U. during the 1990s and the early 2000s. In the late 2000s, however, the United States and China became the locations for the greatest growth in annual capacity additions (see Figure 7.10).

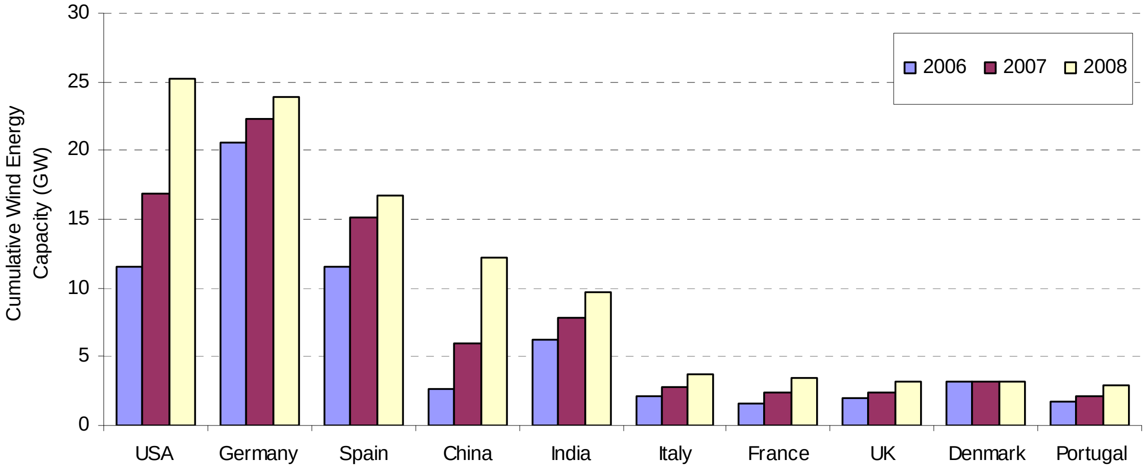


Figure 7.10. Top-10 countries in cumulative wind capacity by the end of 2008 (GWEC, 2009).

Regionally, Europe continues to lead the market with nearly 66 GW of cumulative installed wind energy capacity at the end of 2008, representing 55% of the global total. Despite the continuing growth in Europe, the general trend has been for the wind energy industry to become less reliant on a few key markets over time, and other regions are starting to catch up with Europe (see Figure 7.11). The growth in the European wind energy market in 2008, for example, accounted for just one third of the total new wind energy additions in that year, down from nearly three quarters in 2004. For the first time in decades, more than 60% of the annual wind additions occurred outside of Europe, with particularly significant growth in North America and Asia (GWEC, 2009). Even in Europe, though Germany and Spain have been the strongest markets during the 2000s, there is a trend towards less reliance on these two countries.

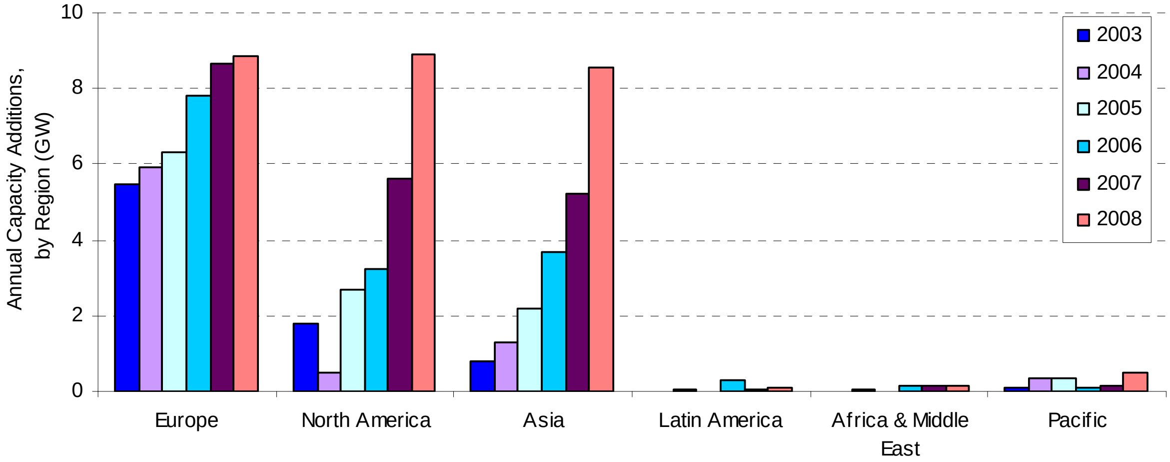


Figure 7.11. Annual wind capacity additions by region (GWEC, 2009).

Despite the increased globalization of wind energy capacity additions, the market remains concentrated regionally. Latin America, Africa, the Middle East, and the Pacific regions have to date installed relatively little wind energy generation capacity. And, even in the regions of significant growth, most of that growth is occurring in a limited number of countries. In 2008, for example, 88% of wind capacity additions occurred in the 10 largest markets, and 54% was concentrated in just two countries: the United States and China.

In both Europe and the United States, wind represents a major new source of electric capacity additions. From 2000 to 2008, wind was the second-largest new resource added in the U.S. (8% of all capacity additions) and E.U. (32% of all capacity additions) in terms of nameplate capacity, behind natural gas, but ahead of coal (Figure 7.12). In 2008, 42% of all capacity additions in the U.S. and 36% of all additions in the E.U. came from wind energy (Figure 7.12). On a global basis, from 2000 through 2008, wind represented roughly 10% of total net capacity additions; in 2008 alone, that figure was roughly 18%.[11]

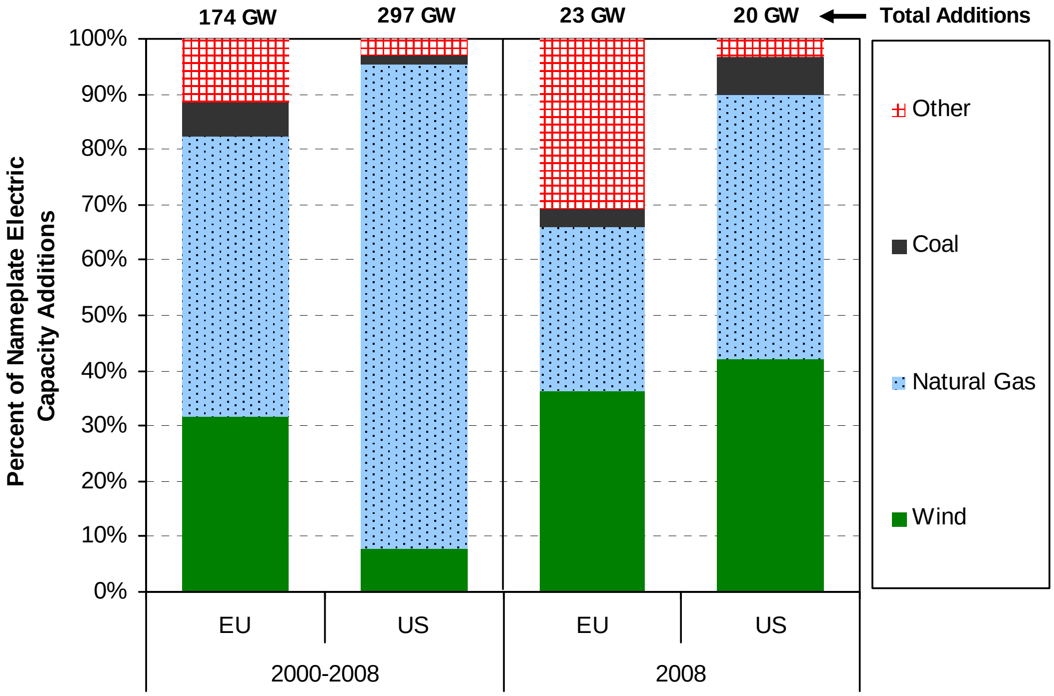


Figure 7.12. Relative contribution of generation types to capacity additions in the E.U. and U.S. (Wiser and Bolinger, 2009).

Though wind energy remains a modest contributor to global electricity supply, a number of countries are beginning to achieve relatively high levels of wind energy penetration in their respective electricity grids as a result of this expansion. Figure 7.13 presents data on end-of-2008 (and end-of-2006/07) installed wind capacity, translated into projected annual electricity supply, and divided by electricity consumption. On this basis, and focusing only on the 20 countries with the greatest cumulative installed wind capacity, end-of-2008 wind capacity is projected to supply roughly 20% of Denmark's electricity demand, 13% of Spain's, 12% of Portugal's, 9% of Ireland's, and 8% of Germany's (Wiser and Bolinger, 2009). In the E.U. as a whole, wind capacity installed at the end of 2008 was able to meet 4.2% of electricity consumption (GWEC, 2009).

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[11] Worldwide capacity additions from 2000 through 2006 come from historical data from the U.S. Energy Information Administration. Capacity additions for 2007 and 2008 are estimated based on U.S. Energy Information Administration forecasts (U.S. EIA, 2009).

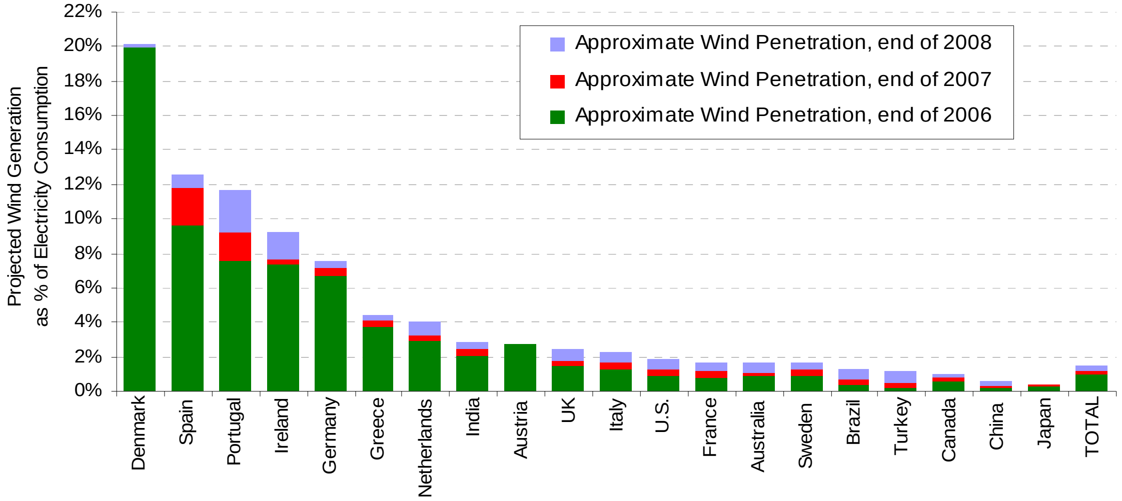


Figure 7.13. Approximate wind energy penetration in the twenty countries with the greatest installed wind capacity (Wiser and Bolinger, 2009).

7.4.3 Industry development

The growing maturity of the wind sector is illustrated not only by wind energy additions, but also by trends in the wind energy industry. In particular, companies from outside the traditional wind industry have become increasingly involved in the sector. There has been a shift in the type of companies developing and owning wind projects, from relatively small independent project developers towards large power generation companies (including electric utilities) and large independent project developers, often financed by investment banks. On the manufacturing side, the increase in the size of the market and the requirement for a substantial investment in expanded production facilities has brought in new players. The involvement of these new and larger players has, in turn, encouraged a greater globalisation of the industry. Manufacturer product strategies are shifting to address larger scale project implementations, higher capacity turbines, and lower wind speeds. More generally, wind's significant contribution to new electric generation capacity investment in several regions has attracted a broad range of players across the industry value chain, from local site-focused engineering firms, to global vertically integrated utilities. The industry's value chain has also become increasingly competitive as a multitude of firms seek the most profitable balance between vertical integration and specialization (BTM, 2009; GWEC, 2009).

The global wind turbine market remains somewhat regionally segmented, with just six countries hosting the majority of wind turbine manufacturing (China, Denmark, India, Germany, Spain, and the U.S.). With markets developing differently, market share for turbine supply has been marked by the emergence of national industrial champions, entry of highly focused technology innovators, and the arrival of new start-ups licensing proven technology from other regions (Lewis and Wiser, 2007). Regardless, the industry continues to globalize: Europe's turbine manufacturers have begun to penetrate North America and Asia, and the growing presence of Asian manufacturers in Europe and North America is expected to become more pronounced in the years ahead (BTM, 2009). Wind turbine sales and supply chain strategies are expected to continue to take on a more international dimension as volumes increase. Already, turbine and component suppliers have an increasing focus on new production facilities in the U.S., China, and India.

Amidst the growth in wind capacity also come challenges. From 2005 through 2008, supply chain difficulties caused by growing demand strained the industry, and prices for turbines and turbine components increased to compensate for this imbalance; commodity price increases and other factors also played a role in pushing wind turbine prices higher (Blanco, 2009; Bolinger and Wiser, 2009). Overcoming supply chain difficulties is not simply a matter of ramping up the production of wind turbine components to meet the increased levels of demand. Large-scale investment decisions are more easily made based on a sound long-term outlook for the industry; but in most markets, both the projections and actual demand for wind energy depend on a number of factors, some of which are outside of the control of the industry, such as political frameworks and policy measures. The impact of the financial crisis in 2008 and 2009 also illustrates the challenges of forecasting future growth, with wind energy additions falling in 2009, thereby at least temporarily easing supply chain bottlenecks.

7.4.4 Impact of policies

The deployment of wind energy must overcome a number of barriers that vary in type and magnitude depending on the wind energy application and region. The most significant barriers to wind energy development are summarized here. Perhaps most importantly, in many regions, wind energy remains more expensive than fossil-fuel generation options, at least if environmental impacts are not monetized. Additionally, a number of other barriers exist that are at least somewhat unique to wind energy. The most critical of these barriers include: (1) concerns about the impact of wind energy's variability on electricity reliability; (2) challenges to building the new transmission infrastructure both on- and off-shore needed to enable access to the most-attractive wind resource areas; (3) cumbersome and slow planning, siting, and permitting procedures that impede wind development; (4) the relative immaturity and therefore high cost of off-shore wind energy technology; and (5) lack of institutional and technical knowledge in regions that have not experienced substantial wind development to this point.

As a result of these issues, growth in the wind energy sector is affected by and responsive to political frameworks and a wide range of government policies. During the past two decades, a significant number of developed countries and, more recently, a growing number of developing nations have laid out RE policy frameworks that have played a major role in the expansion of the wind energy market. An early significant effort to deploy wind energy at commercial scale occurred in California, with a feed-in tariff and aggressive tax incentives spurring growth in the 1980s, fed in large measure by Danish wind technology [TSU: sentence unclear] (Bird *et al.*, 2005). In the 1990s, wind energy deployment moved to Europe, with feed-in tariff policies initially established in Denmark and Germany, and later expanding to Spain and then a number of other countries (Meyer, 2007); renewables portfolio standards have been implemented in other European countries. In the mid to late 2000s, growth in the United States (Bird *et al.* 2005; Wiser and Bolinger, 2009) and China (Li *et al.*, 2007) was based on varied policy frameworks, including renewable portfolio standards, tax incentives, feed-in tariff mechanisms, and government-overseen bidding. Still other policies have been used in a number of countries to directly encourage the localization of wind turbine and component manufacturing (Lewis and Wiser, 2007).

Though economic incentive policies differ, and a healthy debate exists over the relative merits of different approaches, a key finding is that policy continuity and market stability are important (see Chapter 11). Moreover, though it is not uncommon to focus on economic incentive policies for wind energy, as noted above and as discussed elsewhere in this chapter and in Chapter 11, experience shows that wind energy markets are also dependent on resource availability, site planning and approval procedures, operational integration concerns, transmission grid expansion, wind energy technology improvements, and the availability of institutional and technical knowledge in markets unfamiliar with wind energy (IEA, 2009b). For the wind energy industry, these issues have been critical in defining both the size of the market opportunity in each country and the rules for participation in those opportunities. As a result, successful frameworks for the deployment of wind energy have generally included the following elements: support systems that offer adequate profitability and that ensure investor confidence; appropriate administrative procedures for wind energy planning, siting, and permitting; a degree of public acceptance of wind projects to ease project implementation; access to the existing electricity grid and strategic grid planning and new investment for wind energy; and proactive efforts to manage wind energy's inherent variability. In addition, research and development by government and industry has been found to be essential to enabling incremental improvements in on-shore wind energy technology and to driving the improvements needed in off-shore wind technology. Finally, for those markets that are new to wind energy deployment, both knowledge (e.g., wind resource mapping expertise) and technology (e.g., to develop local wind turbine manufacturers) transfer can help facilitate early wind energy installations.

7.5 Near-term grid integration issues

7.5.1 Introduction

The integration of wind energy into electricity systems has become an important topic as wind energy penetration levels have increased (WWEA, 2008; Holttinen *et al.,* 2009). The nature and size of the integration challenge will be system specific and will vary with the degree of wind energy penetration. Nonetheless, the existing literature generally suggests that, in the near term, the integration of increased levels of wind energy is technically and economically manageable, though institutional constraints will need to be overcome. Moreover, increased operating experience with wind energy along with additional research should facilitate the integration of even greater quantities of wind energy without degrading electrical reliability.

The near-term integration issues (approximately the next ten years) covered in this section include how to address wind energy variability and uncertainty, how to provide adequate transmission capacity to connect wind generation to electricity demand centres, and the development of connection standards and grid codes. Longer-term integration may depend on the availability of additional flexibility options to manage high wind energy penetrations, such as mass-market demand response, large-scale deployment of electric vehicles and their associated contributions to system flexibility through controlled battery charging, increased deployment of other storage technologies, and improvements in the interconnections between electric power systems. These longer-term options relate to broader developments within the energy sector that are not specific to wind energy (Doherty and O'Malley, 2006; SmartGrids, 2008), and are addressed in Chapter 8.

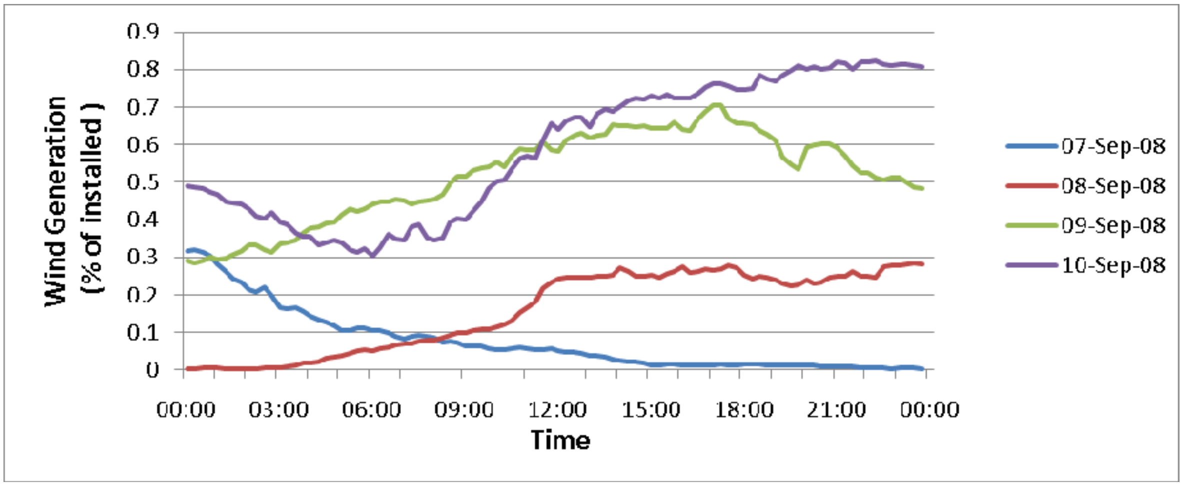
This section begins by describing the specific characteristics of wind energy that present integration challenges (7.5.2). The section then discusses how these characteristics impact issues associated with the planning (7.5.3) and operations [TSU: operation?] (7.5.4) of power systems to accommodate wind electricity, including experience in systems with high wind energy supply. The final section (7.5.5) summarizes the results of various integration studies that have sought to better quantify the technical and economic integration issues associated with increased wind energy penetration.

7.5.2 Wind energy characteristics

The integration of wind energy into power systems is largely based on the same planning and operating mechanisms that are used to ensure the reliable operation of power systems without wind energy, as described in Chapter 8. Several important characteristics of wind energy are different than conventional generation, however, and these characteristics must be considered in the integration [TSU: of] wind energy into power systems.

First, the quality of the wind energy resource and, therefore, the cost of generating wind energy, are location dependent. Sites with high average wind speeds can generate power at much lower cost than sites with lower-quality wind resources, and the regions with the best wind energy resources may not be situated near high demand regions, increasing the need for additional transmission infrastructure to bring wind energy from the best wind resource sites to electricity demand centres.

Second, wind energy is weather dependent and therefore variable. The output of a wind project varies from zero to its rated capacity depending on the prevailing weather conditions; Figure 7.14 illustrates this variability by showing the output of wind projects in Ireland over four consecutive days. The most relevant characteristics of wind energy variability for power system *operations* is the rate of change in wind project output over different time periods; apparent in Figure 7.14 is that wind energy changes much more dramatically over longer periods (multiple hours) than it does in very short periods (minutes). The most relevant characteristic of wind variability for the purpose of power sector *planning*, on the other hand, is the correlation of wind energy output with the periods of time when power system reliability is at greatest risk, typically periods of high electricity demand. This correlation affects the capacity credit assigned by system planners to wind projects, as discussed further in Section 7.5.3.3.



Source: www.eirgrid.com

Figure 7.14. Wind energy supply as a proportion of installed wind capacity in Ireland on four consecutive days.

Third, in comparison with conventional generation, wind energy has lower levels of predictability. Forecasts of wind energy production over longer periods (multiple hours to days) allow for more opportunities to manage variability. Forecasts, however, are less accurate over longer forecast horizons than for shorter periods (Giebel et al., 2006); Figure 7.15 illustrates different forecasting errors over a horizon of up to 36 hours, based on several different forecasting methods.

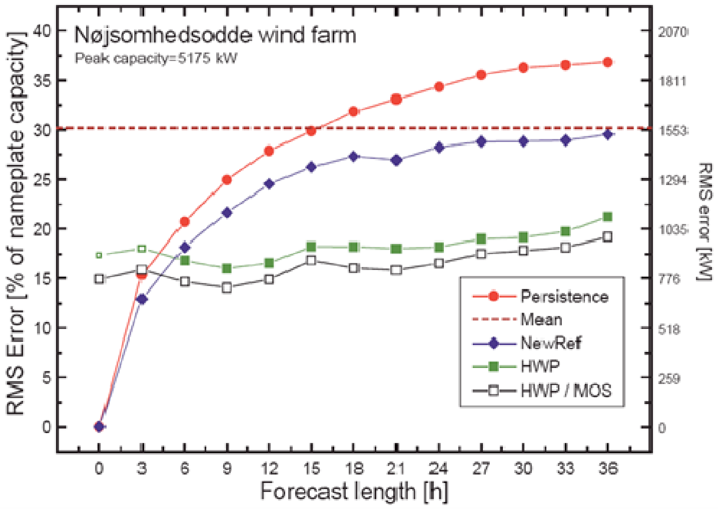


Figure 7.15. Root Mean Square (RMS) error of wind power forecasts for different forecast horizons using different forecasting methods (Giebel *et al*., 2006).

The variability and predictability of wind energy in aggregate depends, in part, on the degree of correlation between geographically dispersed wind projects. This correlation, in turn, depends on the geographic deployment of wind projects and the regional characteristics of wind patterns. Generally, the output of wind projects that are further apart are less correlated, and variability over shorter time periods (minutes) is less correlated than variability over longer time periods (multiple hours) (Wan *et al*., 2003; Holttinen, 2005; Sinden, 2007). The decrease in correlation with distance leads to much less variability (smoothing effect) and much more accurate forecasts of aggregated wind projects over a region than the scaled output of a single wind project (nonetheless, in absolute terms, variability and forecast errors increase with increasing quantities of wind energy). The prevailing weather patterns of a region will have a large influence on all these characteristics: variability, forecasting, and the impact of geographical dispersion.

Finally, the electrical characteristics of some wind generators differ from the synchronous generators found on most conventional power projects. The variable speed wind generation technologies being installed in most wind projects (doubly fed induction generators (DFIG) and synchronous generator with a full power convertor) essentially decouple the rotating masses (turbine and generator) from the electric power system. This decoupling typically results in no inertial response (Mullane and O'Malley, 2005). Additional control capability, however, can be added to these generators to provide inertial response (Morren *et al*., 2006). As discussed in later sections, the lack of inertial response without specific additional controls is an important consideration for system planners since less overall inertia increases the challenges related to maintaining stable system operation (Gautam *et al*., 2009).

7.5.3 Planning power systems with wind energy

Ensuring the reliable operation of power systems in real-time requires detailed system planning over the time horizons required to build new generation or transmission infrastructure. Planners must evaluate the adequacy of transmission to allow interconnection of new generation and the adequacy of generation to maintain a balance between supply and demand under a variety of operation conditions (see Chapter 8). Three issues deserve attention when considering increased reliance on wind energy: the need for accurate power system models of wind projects, the creation of interconnection standards (i.e., grid codes) that account for the characteristics of wind energy, and consideration of new wind [TSU: energy] generation in evaluating transmission and generation resource adequacy.

7.5.3.1 Power system models

Power system models are used extensively in planning to evaluate the ability of the power system to accommodate new generation, changes in demand, and changes in operational practices. An important role of power system models is to demonstrate the ability of a power system to recover from severe events or contingencies. Generic models of conventional synchronous generators have been developed and validated over a period of multiple decades. These models are used inside industry standard software tools (e.g., PSSE, DigSilent, etc.) to study how the electric power system and all its components behave during system events or contingencies. Similar generic models of wind generators and wind projects are in the process of being developed and validated. Because wind turbines are non-standard when compared to conventional synchronous generators, this modelling exercise requires significant effort. There has been considerable progress in this area. This process is not complete, however, and the continued development of wind energy [TSU: technology] will require improved and validated models to allow planners to assess the capability of power systems to accommodate additional wind projects (Coughlan *et al*., 2007; NERC, 2009).

7.5.3.2 Grid codes

Interconnection standards, or grid codes, are put in place to prevent equipment or facilities that interconnect with a power system from adversely affecting reliability. These grid codes are developed by power system planners, regulators, and power system operators depending on the jurisdiction. Grid codes may also specify minimum requirements that facilities or equipment must meet to help maintain power system operation during normal operation and contingencies. Power system models and operating experience are used to develop these requirements. In some cases, the unique characteristics of specific generation types are addressed in grid codes. The unique characteristics of wind turbines, for example, have resulted in dedicated “wind” grid codes in some locations (Singh and Singh, 2009).

Grid codes often require “fault ride-through” capability, or the ability of a project to remain connected and operational during brief but severe changes in power system voltage. The addition of fault ride-through requirements for wind projects in grid codes was in response to the increasing penetration of wind energy and the significant size of individual wind projects in many systems. When wind turbines are only interconnected with the power system as single turbines or in small numbers, systems can typically maintain reliable operation if these wind turbines shut-down or disconnect from the power system for protection purposes in response to fault conditions. As project sizes and the penetration of wind energy has increased, however, system planners have specified that wind projects should continue to remain operational during faults and meet minimum fault ride-through standards similar to other large conventional projects. Reactive power control to help manage voltage is also often required by grid codes. Wind turbine inertial response to increase system stability after disturbances is less common, but is beginning to be required in some grid codes (e.g., Hydro-Quebec TransEnergie, 2006).

7.5.3.3 Transmission infrastructure and resource adequacy evaluations

The addition of large quantities of wind energy to the power system will require upgrades to the transmission system. Accurate transmission adequacy evaluations must account for the locational dependence of wind resources, the relative smoothing benefits of aggregating wind over a large area, and the transmission capacity required to manage the variability of wind energy. As described in more detail in Chapter 8, one of the primary challenges with transmission expansion is the long time it takes to plan, permit, and construct new transmission relative to the time it takes to add new wind projects. Enabling high penetration of wind energy will therefore likely require proactive rather than reactive transmission planning. The need for additional transmission investment to enable wind energy supply is discussed further in Chapter 8.

Generation resource adequacy evaluations routinely assess the capability of generating resources to reliably meet electricity demand. Planners evaluate the long-term reliability of the power system by estimating the probability that the system will be able to meet expected demand in the future, as measured by the load carrying capability of the system. Each generation resource contributes some fraction of its name-plate capacity to the overall capability of the system, as indicated by the capacity credit assigned to the resource; the capacity credit is greater when generation output is tightly correlated with periods of time when there is a high risk of generation shortage. For example, a 100 MW project that is assigned a capacity credit of 90% adds 90 MW to the total ability of the system to serve demand. The capacity credit of a generator is a "system" characteristic in that it is determined not only by the generator's characteristics but also by the characteristics of the system to which that generator is connected.

The contribution of wind energy toward long-term reliability can be evaluated using standard approaches, and wind generators are typically found to have a capacity credit of 5-40% of name-plate capacity (Holttinen *et al.*, 2009). The correlation between wind energy output and electrical demand is an important determinant of the capacity credit of an individual wind generator, as is the correlation between the output of different wind projects. In many cases, wind resources are uncorrelated or are weakly negatively correlated with periods of high electricity demand, reducing the capacity credit of wind projects; this is not always the case, however, and wind generation in the UK has been found to be weakly positively correlated with periods of high demand (Sinden, 2007). These correlations are highly system specific as they depend on the diurnal and seasonal characteristics of both wind generation and electricity demand.

A final important characteristic of the capacity credit for wind energy is that its value decreases as wind penetration levels rise (see figure presented in Chapter 8). This characteristic is driven by the correlation between wind project output; the higher the correlation between the output of individual wind projects the lower the capacity credit as wind energy penetration levels increase. Aggregating wind projects over larger areas reduces the correlation between wind project output and can slow the decline in capacity credit, though adequate transmission capacity is required to aggregate wind projects over larger areas in this manner (Tradewind, 2009).[12]

7.5.4 Operating power systems with wind energy

7.5.4.1 Integration, flexibility, and variability

Because wind energy is produced with a near-zero marginal cost, wind energy is typically used to meet demand when wind power is available, thereby displacing the use of conventional generators that have higher marginal operating costs. Power system operators therefore primarily dispatch conventional generators to meet demand minus any available wind generation (net demand).

As wind energy penetration grows, the variability and limited predictability of wind energy will result in an overall increase in the magnitude of changes in net demand and a decrease in the minimum net demand. Figure 7.16 shows that, at relatively low levels of wind energy penetration, the magnitude of changes in *net demand*, as shown in the ramp duration curve, is similar to the magnitude of changes in *demand* (Figure 7.16(c)), but at high levels of wind energy penetration the changes in net demand are greater than changes in total demand (Figure 7.16(d)). The figure also

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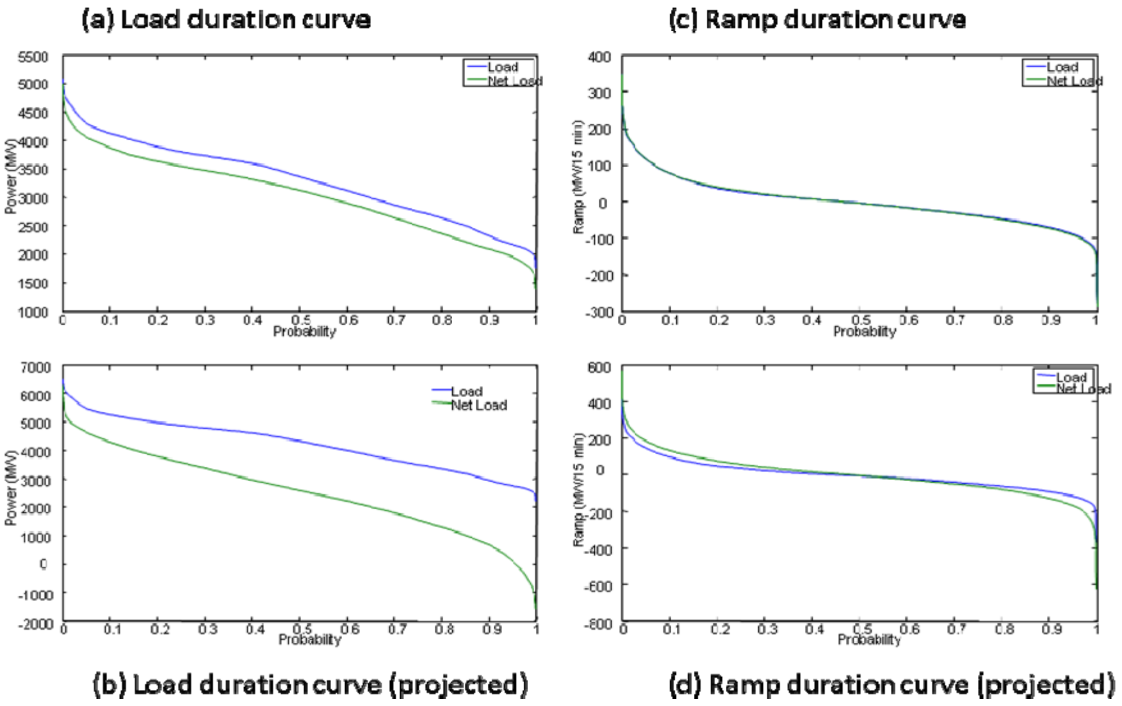
[12] Generator resource adequacy evaluations are also beginning to include the capability of the system to provide adequate flexibility and operating reserves to accommodate more wind generation (NERC, 2009). The increased demand from wind for operating reserves and flexibility is addressed in Section 7.5.4.

shows that, at high levels of wind energy, the magnitude of net demand across all hours of the year is lower than total demand, and that in some hours the net demand is near or below zero (Figure 7.16(b)).



Source: *www.eirgrid.com*

Figure 7.16. Load and ramp duration curves for Ireland in (a,c) 2008, and (b,d) projected for high wind energy penetration levels[13].

As a result of these trends, increased wind energy will require that conventional generating units operate in a more flexible manner than required without wind energy. In the near term, it is expected that the increase in minute-to-minute variability will be relatively small and therefore inexpensive to manage in large power systems. The more significant operational challenges relates to the variability and commensurate increased need for flexibility to manage changes in wind generation over 1 to 6 hours. Incorporating state-of-the-art forecasting of wind energy over multiple time horizons into power system operations can reduce the need for flexibility and operating reserves and has been found to be critical to economically and reliably operating power systems with high levels of wind energy. Even with high-quality forecasts, however, additional start-ups and shut-downs, part-load operation, and ramping will be required from conventional units to maintain the supply/demand balance (Göransson and Johnsson, 2009; Troy and O'Malley, 2010).

Though this additional flexibility comes at a cost, proper incentives can ensure that the operational flexibility of conventional generators is made available to system operators. Many regions, for example, have day-ahead, intra-day, or hour-ahead markets for energy as well as markets for reserves and balancing energy. In these circumstances, any increase in the demand for flexibility and reserves caused by increased levels of wind energy will create enhanced incentives for generators and other resources to allocate available flexibility or capacity to the system. The creation of robust markets for such flexibility services will therefore reduce the cost impacts of

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[13] Projected penetration level curves are based on scaled of 2008 data (demand is scaled by 1.27 and wind is scaled on average by 7). Ramp duration curves show the cumulative probability distributions of 15-minute changes in demand and net demand.

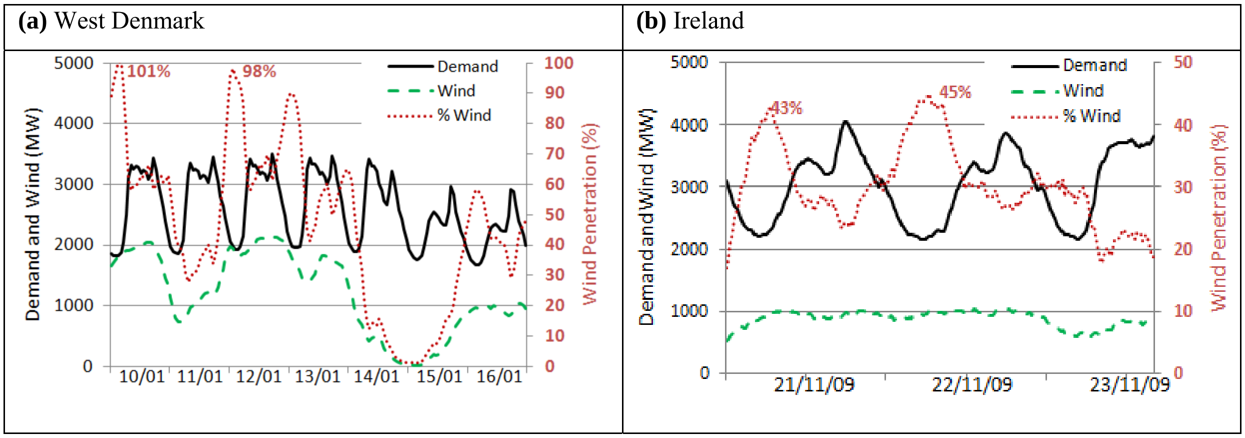
integrating wind generation (Smith *et al.*, 2007b). System operators can also increase access to this existing flexibility through shorter scheduling periods: sub-hourly, or fast energy markets, provide more access and lower costs to accommodate wind energy than do markets based on hourly schedules (Kirby and Milligan, 2008b). Hydropower units, electrical storage units, and various forms of demand response can all be used to further facilitate the integration of wind energy. Additionally, systems with high penetrations of wind energy may need to ensure that new conventional plants are flexible enough to accommodate expected wind production. Wind projects, meanwhile, can provide some flexibility by curtailing output. Though curtailment of wind output is a simple and often times readily available source of flexibility, it is also expensive because wind projects have low operating costs; as a result, wind output curtailment is not likely to be used extensively at low levels of wind energy supply.

7.5.4.2 Practical experience in integrating wind energy

Actual operating experience in different parts of the world demonstrates that wind energy can be reliably integrated into power systems (Söder *et al.*, 2007). The three examples reported here demonstrate the challenges associated with this integration, and the methods used to manage the additional variability, uncertainty, and transmission system impacts associated with wind energy. Naturally, these impacts and management methods vary across regions for reasons of geography, power system design, and regulatory structure.

Denmark has the largest wind energy penetration of any country in the world, with wind energy supplies of 20% of total annual electrical demand (Figure 7.17). The Danish example demonstrates the value of access to markets for flexible resources and strong transmission connections to neighbouring countries. The Danish transmission system operator operates its system without serious reliability issues in part because Denmark is well interconnected to two different synchronous electrical systems. Those markets help the operator manage wind energy output variability. The interconnection with the Nordic system, in particular, provides access to flexible hydropower resources. Balancing the Danish system is much more difficult during periods when one of the interconnections is down, however, and more flexibility is expected to be required if Denmark markedly increased its wind energy supply (EA Energianalyse, 2007).

In contrast to the strong interconnections of the Danish system with other systems, Ireland has a single synchronous system; it is of similar size system to the Danish system but interconnection capacity is limited to a single 400 MW link. Wind capacity installed at the end of 2009 was capable of generating 11% of Ireland's electricity, and the Irish system operators have successfully managed that level of wind energy supply. The large daily variation in electricity demand in Ireland, combined with the isolated nature of the Irish system, has resulted in a very flexible electricity system that is particularly well suited to integrating wind energy. As a result, despite the lack of significant interconnection capacity, the Irish system has successfully operated with instantaneous levels of wind energy supply of over 40%. Nonetheless, it is recognized that as wind penetration levels increase further, many new challenges will arise. Of particular concern is the possible lack of inertial response of wind turbines without additional turbine controls (Doherty *et al.*, 2010), the need for greater flexibility to maintain supply-demand balance, and the need to build substantial amounts of additional high-voltage transmission (AIGS, 2008). Moreover, in common with the Danish experience, much of the wind energy is and will be connected to the distribution system, requiring attention to reactive power control issues (Vittal *et al.*, 2010). Figure 7.17 illustrates the high levels of wind penetration that exist in Ireland and West Denmark.



Source: (a) www.energinet.dk; (b) www.eirgrid.com

Figure 7.17. Wind energy, electricity demand, and instantaneous penetration level in (a) West Denmark for a week in January 2005, and (b) Ireland for three days in November 2009.

The Electric Reliability Council of Texas (ERCOT) operates a synchronous system with a peak demand of nearly 65 GW, and with a wind penetration level of more than 5% at the end of 2008. ERCOT's experience demonstrates the importance of incorporating wind energy forecasts into system operations, and the need to schedule adequate reserves to accommodate system uncertainty. During February 26, 2008 a combination of factors led ERCOT to implement its emergency curtailment plan. On that day, ERCOT experienced a decline in wind energy output of 1,500 MW over a three hour period, roughly 30% of the nameplate capacity of installed wind capacity (Ela and Kirby, 2008; ERCOT, 2008). The event was exacerbated by the fact that scheduling entities - which submit updated resource schedules to ERCOT one hour prior to the operating hour - consistently reported an expectation of more wind generation than actually occurred. A state-of-the-art forecast was available, but was not yet integrated into ERCOT system operations, and that forecast predicted the wind event much more accurately. As a result of this experience, ERCOT accelerated its schedule for incorporating the advanced wind energy forecasting system into its operations.

7.5.5 Results from integration studies

A number of high-quality studies of the increased transmission and generation resources required to accommodate wind energy have been completed around the world. These studies typically quantify the costs and benefits of integrating wind into power systems. The costs include the need for transmission and estimates of the change in operating costs required to accommodate the increased variability and unpredictability caused by wind generation. The benefits include reduced fossil fuel usage and CO_2 emissions. The results of these studies demonstrate that the cost of integrating 10% to 20% wind into the power system is, in most systems, modest but not insignificant.

There are a plethora of wind integration studies with a wide variety of methodologies (Gross *et al.*, 2007; Smith *et al.*, 2007a; Holttinen *et al.*, 2009). As there are many different impacts, positive and negative, each study includes some combination of the following:

- reduction in operating costs because of reduced fossil fuel usage
- additional operational costs from system balancing
- increase in reserve requirements for wind energy
- capacity credit of wind energy
- reinforcements/extensions needed in the transmission grid

- impacts of wind energy on the stability of the transmission system
- impacts of different measures to mitigate variability and uncertainty
- impacts of wind energy on the operation of conventional power plants
- impacts of wind energy on CO_2 emissions

Addressing all impacts requires several different simulation models that operate over different time scales, and most studies therefore focus on only a subset of the potential impacts. The results of wind integration studies will also inherently differ from one power system to another simply due to pre-existing differences in system designs and regulatory environments. Important differences include generation capacity mix and the flexible [TSU: flexibility] of that generation, the variability of demand, and the strength and breadth of the transmission system. Study results also differ because no accepted standard methodology has been developed for these studies, though significant progress has been made in developing agreement on many high-level study design principles (Holttinen *et al.*, 2009).

One of the most significant challenges in executing these studies is simulating wind data at high-time-resolutions for a chosen future wind energy penetration level and for a sufficient duration for the results of the analysis to be statistically reliable. The data are then used in a power system simulation to mimic system operations. Simulations can be used to quantify the costs, emissions savings, and the need to build transmission under a high-wind-energy future. The first-generation integration studies used models that were not designed to fully reflect the variability and uncertainty of wind energy, resulting in studies that addressed only parts of the larger system. More recent studies have used models that can incorporate the uncertainty of wind energy, from the day-ahead time scale to some hours ahead of delivery (Barth *et al.*, 2006). Increasingly, integration studies are simultaneously simulating high wind scenarios in entire synchronized systems (not just individual, smaller balancing areas) (NREL, 2010; EWIS, 2010).

Notable examples of wind integration studies include those conducted in Ireland and the U.S. state of Minnesota. In Ireland, the All Island Grid Study (AIGS, 2008) evaluated five energy supply portfolios with penetration levels of up to 42% RE (34% wind) across a large set of parameters including cost and emissions. The findings confirmed that up to 42% RE is feasible, but that a multitude of technical issues would need to be overcome. Perhaps most important was the need to build significant amounts of new high-voltage transmission; additional transmission investment costs were estimated to be approximately US$178 (2005$) per kW of wind. Other issues that would need to be addressed include reactive power control and system inertia. The cost of the portfolio with the highest wind energy penetration (34%) was modestly more expensive (7% more) than the portfolio with the lowest level of wind penetration (16%). At the same time, the portfolio with the highest wind penetration had 25% less CO_2 emissions than the portfolio with low penetration.

In Minnesota, a detailed wind integration study was completed in 2006 (EnerNex Corp., 2006). This study looked at the operational integration costs associated with wind energy, assuming that integration occurred within the context of a well-developed energy market operating in the Midwest Independent System Operator (MISO) territory. The MISO territory covers parts of 14 states, with a peak electricity demand in excess of 115 GW. The assumed Minnesota demand of 21 GW in the year 2020 was served by up to 6 GW of wind capacity. The study results show that 25% wind electricity in Minnesota can be reliably accommodated by the power system, if adequate transmission is available. The highest incremental cost of wind integration associated with this future was estimated to be $4.40/MWh of delivered wind energy, including the cost of additional reserves. Balancing area consolidation within Minnesota, the overall size of the MISO market, and wind project output forecasting were shown to reduce wind integration costs and challenges.

The costs reported by these two studies broadly agree with the results of other significant integration studies conducted in the U.S. and Europe. The estimated increase in short-term reserve requirements in eight studies summarized in an IEA report (Holttinen *et al.*, 2009) has a large range: 1-15% of installed wind energy capacity at 10% wind energy penetration and 4-18% of installed wind energy capacity at 20% wind energy penetration. The higher results are generally from studies that assume that day-ahead uncertainty or four-hour variability of wind energy output is handled with short-term reserves; markets that are optimized for wind energy will generally not operate in this fashion. Notwithstanding these variations in results and methods, the studies find that, in general, a wind energy penetration of up to 20% can be accommodated with increased system operating costs of roughly 1.4–5.6 US$/MWh of wind energy produced, or roughly 10% or less of the levelized generation cost of wind energy.

In addition to these increased operating costs, several broad assessments of the need for and cost of transmission for wind energy have found modest, but not insignificant, costs. The transmission cost for 300 GW of wind in the United States was estimated to add about 10-15% to the levelized cost of wind energy (U.S. DOE, 2008). Similar cost estimates were reached from a much more detailed assessment of the transmission needs of a 20% wind energy scenario for the Eastern Interconnection of the U.S. (JCSP, 2009). Large-scale transmission for wind energy has also been considered in Europe (Czisch and Giebel, 2000) and China (Lew *et al.*, 1998). Results from country specific transmission assessments for wind energy in Europe lead to varied estimates of the cost of transmission; Auer *et al.* (2004) and EWEA (2005) identified transmission costs for a number of European studies, with cost estimates that are somewhat lower than those found in the U.S. (Mills *et al.*, 2009). Holttinen *et al.* (2009) review wind energy transmission costs from several European national case studies, and find those costs to range from 3-13% of the levelized generation cost of wind energy. Finally, a European-wide study identified several transmission upgrades between nations and between high quality off-shore wind resource areas that would reduce transmission congestion and ease wind integration for a 2030 scenario. The study highlights the benefits that a DC [TSU: abbr.] network of off-shore transmission would provide rather than building radial lines between individual off-shore wind farms and on-shore connection points (Tradewind, 2009).

7.6 Environmental and social impacts

Wind energy has significant potential to reduce GHG emissions, together with the emissions of other air pollutants, by displacing fossil fuel-based electricity generation. Because of the relative maturity (Section 7.3) and cost (Section 7.8) of the technology, wind energy can be immediately deployed on a large scale (Section 7.9), enabling significant reductions in emissions in the short- to medium-term. As with other industrial activities, however, wind energy also has the potential to produce some negative impacts on the environment and on human beings, and many local and national governments have established planning, permitting, and siting requirements to minimize those impacts. These potential concerns need to be taken into account to ensure a balanced view of the advantages and disadvantages of wind energy. This section summarizes the best available knowledge on the most relevant environmental net benefits of wind energy (7.6.1), while also addressing more specifically ecological (7.6.2) and human impacts (7.6.3), public attitudes and acceptance (7.6.4), and processes for minimizing social and environmental concerns (7.6.5).

7.6.1 Environmental net benefits of wind

The environmental benefits of wind energy come primarily from a reduction of emissions from conventional electricity generation. However, the manufacturing, transport, and installation of wind turbines induces some indirect negative effects, and the variability of wind generation also impacts the operations and emissions of conventional plants; such effects need to be subtracted from the gross benefits to find the net environmental benefits of wind energy. As shown below, these latter effects are modest compared to the net GHG reduction benefits of wind energy.

7.6.1.1 Direct impacts

The major environmental benefits of wind energy result from displacing electricity generation from conventional, fossil-fuel powered electricity generators, as the operation of wind turbines does not directly emit greenhouse gases or other air pollutants such as SO_2, NO_x, CO, NMVOCs, particulates, or heavy metals. Estimating the emissions reduction benefits of wind is complicated by the operational characteristics of the electricity system and the investment decisions that are made in new plants to economically meet electricity load (Deutsche Energie-Agentur, 2005; NRC, 2007). In the short-run, increased wind energy will typically displace the operations of existing fossil plants that are otherwise on the margin. In the longer-term, new generating plants may be needed, and the presence of wind generation will influence what types of power plants are built (Kahn, 1979; Lamont, 2008). Depending on the characteristics of the electricity system into which wind energy is integrated, and the amount of wind energy generation, the reduction of air emissions may be substantial. For example, in the largely coal-based German electricity system, the installed wind energy capacity of about 22 GW in 2007 produced roughly 40 TWh of electricity, leading to a reduction in GHG emissions of 34 Mt CO_2 (Federal Ministry for the Environment, 2008), around 10% of the total GHG emissions of the German power sector (Umweltbundesamt, 2009).[14]

In addition to reducing GHG and air pollutant emissions, wind energy also reduces cooling water demands from the operation of conventional power plants. Wind energy can avoid the need for cooling water that would otherwise be used by electricity production from conventional steam generators; in addition, waste ash produced from coal generation will be avoided, as can some of the adverse impacts from coal mining and natural gas drilling.

7.6.1.2 Indirect lifecycle impacts

One indirect impact of wind energy arises from the release of GHGs and air pollutants during the manufacturing, transport, and installation of wind turbines, and their subsequent decommissioning. Life-cycle assessment (LCA) procedures, based on ISO 14040 and ISO 14044 standards (ISO, 2006), have been used to analyze these impacts. Though these studies may include a range of impact categories, LCA studies for wind energy have often been used to determine the life-cycle GHG emissions per unit of wind-electricity generated (allowing for full fuel-cycle comparisons with other forms of electricity production) and the energy payback time of wind energy systems (i.e., the time it takes a wind turbine to generate an amount of electricity equivalent to that used in its manufacture and installation). The results of a number of LCA studies for wind energy are summarized in Table 7.3.

Table 7.3. Wind energy carbon intensity and energy payback from various LCA studies

Article	**Wind Turbine Size**	**Location**	**Capacity Factor**	**Energy Payback (years)**	**Carbon Intensity (gCO_2/kWh)**
DWTMA (1997)	0.6 MW	on-shore	n/a	0.25	n/a
Schleisner (2000)	0.5 MW	on-shore	43.5%	0.26	9.7
Voorspools (2000)	0.6 MW	on-shore[1]	n/a	n/a	27
Jungbluth et al. (2005)	0.8 MW	on-shore	20%	n/a	11

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[14] Total electricity demand in Germany in 2007 was 541 TWh (with 138 GW of installed capacity), and total power-sector CO_2 emissions were 386 Mt (Bundesministerium fuer Wirtschaft und Technologie, 2009).

Pehnt (2006)	1.5 MW	on-shore	n/a	n/a	10.2
Martínez et al (2009)	2.0 MW	on-shore	23%	0.40	n/a
Elsam (2004)	2.0 MW	on-shore	n/a	0.65	7.6
Vestas (2006)	3.0 MW	on-shore	30%	0.55	4.6
Tremeac and Meunier (2009)	4.5 MW	n/a	30%	0.58	15.8
Schleisner (2000)	0.5 MW	off-shore	40%	0.39	16.5
Voorspools (2000)	0.6 MW	off-shore*	n/a	n/a	9.2
Jungbluth et al. (2005)	2.0 MW	off-shore	30%	n/a	13
Elsam (2004)	2.0 MW	off-shore	n/a	0.75	7.6
Pehnt (2006)	2.5 MW	off-shore	n/a	n/a	8.9
Vestas (2006)	3.0 MW	off-shore	54%	0.57	5.2
EPD Vattenfall (2003)	Not stated	n/a	n/a	n/a	14

* In Voorspools (2000), on-shore is described as "inland" and off-shore is described as "coastal"

The reported energy payback (in years) and carbon intensity (in gCO_2/kWh) of wind energy are low, but vary somewhat among published LCA studies, reflecting both methodological differences and differing assumptions about the life cycle of wind turbines. The carbon intensity of wind estimated by the studies included in Table 7.3 ranges from 4.6 to 27 gCO_2/kWh. Where studies have identified the significance of different stages of the life cycle of a wind project, it is clear that emissions from the manufacturing stage dominate overall life-cycle GHG emissions (e.g., Jungbluth *et al.,* 2005). Energy payback times for the studies presented in Table 7.3 suggest that the embodied energy of modern wind turbines is repaid in 3 to 9 months of operation.

7.6.1.3 Indirect variability impacts

Another concern that is sometimes raised is that the temporal variability and limited predictability of wind energy will increase the short-term balancing reserves required for an electric system operator to maintain reliability (relative to the balancing reserve requirement without wind energy). Short-term reserves are generally provided by generating plants that are online and synchronized with the grid, and plants providing these reserves may be part-loaded to maintain flexibility to respond to short-term fluctuations. Part-loading fossil fuel-based generators decrease the efficiency of the plants and therefore create a fuel efficiency and GHG emissions penalty relative to a fully-loaded plant. Analyses of the emissions benefits of wind do not always account for this effect.

The UK Energy Research Centre performed an extensive literature review of the costs and impacts of variable generation; over 200 reports and articles were reviewed (Gross *et al.,* 2007). The review included a number of analyses of the fuel savings and GHG emissions benefits[15] of wind generation that account for the increase in necessary balancing reserves and the reduction in part-load efficiency of conventional plants. The efficiency penalty due to the variability of wind in four studies that explicitly addressed the issue was negligible to 7%, for up to 20% wind electricity penetration (Gross *et al.,* 2006). In short, for moderate levels of wind penetration, "there is no evidence available to date to suggest that in aggregate efficiency reductions due to load following amount to more than a few percentage points" (Gross and Heptonstall, 2008).

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[15] Because CO_2 emissions are generally proportional to fuel consumption for a single plant, the CO_2 emissions penalty is similar to the fuel efficiency penalty.

7.6.1.4 Net environmental benefits

The overall net balance of positive and negative environmental and health effects of wind energy is documented by the difference in estimated external costs for wind energy and other electricity production options, as shown in Figure 7.18 for Germany. This figure is based on the results of Krewitt and Schlomann (2006), and contains monetized figures for climate change damages, human health impacts, material damages, and agricultural losses. Krewitt and Schlomann (2006) also qualitatively assess the direction of possible impacts associated with other damage categories (ecosystem effects, large accidents, security of supply, and geopolitical effects), finding that the net benefits of RE sources tend to be underestimated by not including these impacts in the monetized results. As such, though the figure does not include all ecological effects, it shows the overall significance of the difference between the environmental benefits and the environmental burdens of wind energy. Similar results are found in the externalities literature of other countries, e.g. in the ExternE project of the E.U. comparing the external costs of different fuel cycles and different countries (Bickel and Friedrich, 2005).

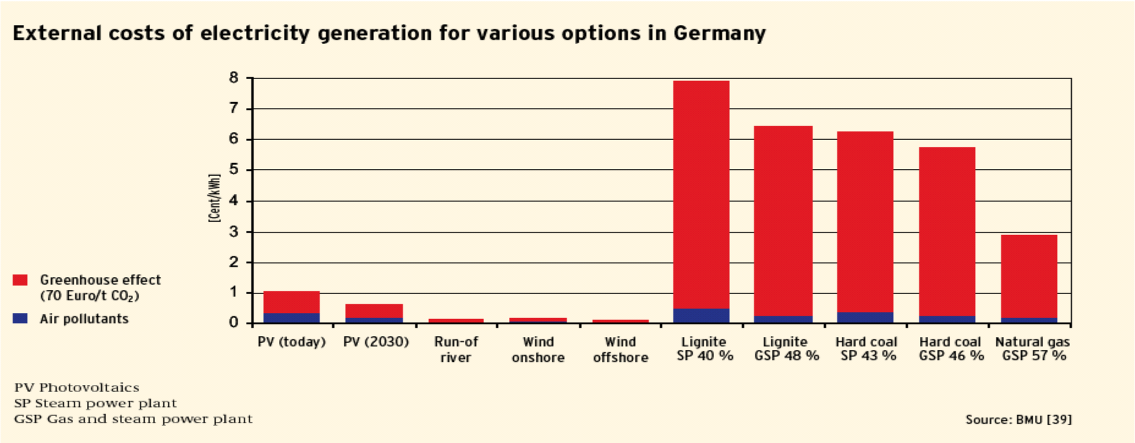

Figure 7.18. External costs of electricity generation for various options in Germany (Federal Ministry for the Environment, 2008, based on Krewitt and Schlomann, 2006).

7.6.2 Ecological impacts

Though the external costs of wind energy are low compared to other forms of electricity generation (Figure 7.18), there are ecological impacts that need to be taken into account when assessing wind energy. Following the National Research Council of the U.S. National Academies (NRC, 2007) and Michel *et al.* (2007), the primary ecological impacts from on-shore wind projects include direct bird and bat fatalities, and the disruption of ecosystem structure. For off-shore wind projects, impacts on benthic resources, fisheries, and marine life more generally must also be considered. Finally, the possible impacts of wind project development on the local climate have also been the focus of some study.

7.6.2.1 Direct bird and bat fatalities

Direct bird and bat fatalities are among the most recognized ecological impact categories for on-shore wind projects (e.g., NRC, 2007; EWEA, 2009). Though these impacts have generated a high level of interest, they are highly site specific and need to be put into the context of other bird fatalities caused by human activities. Erickson *et al.* (2005), for example, estimated that over 680 million annual bird fatalities are due to collisions with human-made structures in the United States, and 150 million from other anthropogenic causes. That study concluded that wind generation in the U.S. is responsible for 0.003% of anthropogenic avian mortality; for the year 2003, about 17,500 wind turbines in the U.S. led to 20,000 to 37,000 avian fatalities. It has also been very-roughly estimated that wind projects cause 0.28 avian fatalities per GWh, while nuclear power generation causes about 0.42 and coal based electricity causes about 5.2 fatalities per GWh; the strongest impact is due to effects of climate change on bird life (Sovacool, 2009).

The U.S. National Research Council found a wide range of bird fatality estimates reported in the literature on U.S. wind projects (NRC, 2007). Bird mortality estimates from these studies range from 0.98 to 7.7 per turbine and year, while the range per MW of installed capacity is even wider, from 0.95 to 11.67 bird fatalities per MW and year (NRC, 2007). Erickson *et al.* (2005), meanwhile, report 2.11 avian deaths per wind turbine in the U.S., while a study by EHN (2003) conducted on 18 wind projects in Navarra, Spain showed an annual mortality of 0.13 birds per wind turbine. Though most of the bird fatalities reported are of songbirds (Passeriformes), which are the most abundant bird group in terrestrial ecosystems (NRC, 2007), raptor fatalities may be of greater concern as their numbers tend to be relatively small. Raptor fatalities have been reported separately in many U.S. studies. Compared to songbird fatalities resulting from wind turbines, raptor fatalities are relatively low, with zero to 0.07 fatalities per turbine and year being reported (NRC, 2007). As should be clear from the data presented here, bird fatality rates are highly project-specific, and vary with site characteristics, turbine design, and turbine size (NRC, 2007).

Bat fatalities have not been researched as extensively as bird fatalities connected to wind energy development, and data allowing reliable assessments of bat fatalities are limited (NRC, 2007). Studies for the U.S. show a wide range of results, with observed bat fatalities ranging from 0.8 to 41.1 bats per MW (per year) (NRC, 2007). The specific role of different influences such as site characteristics, weather conditions, turbine design, and turbine size remain uncertain due to the lack of extensive and comparable studies; additional research is therefore being conducted to better assess these impacts, and their possible mitigation. In the U.S., for example, the Bats and Wind Energy Cooperative was formed in 2004 to address this issue. Results of one study demonstrated that curtailing operation of wind turbines during low wind situations resulted in bat fatality reductions averaging 73% (and ranging from 53% to 87%) compared to fully operational turbines; these results indicated that changing the cut-in speed of turbines can contribute to significant reductions in bat fatalities (Arnett *et al.*, 2009). Similar results have been found at studies conducted in Canada and Germany.

7.6.2.2 Ecosystem structure impacts

Ecosystem impacts, and in particular impacts on habitats of various species, depend largely on the ecosystem into which wind energy facilities are integrated. Wind projects are often installed in agricultural landscapes or on brown-field sites. In such cases, relatively few ecosystem structure impacts are to be expected. In some regions, wind projects are increasingly being sited on forested ridges; in these instances, the construction of access roads and forest clearings for turbine foundations and power lines may have substantial impacts. The existing literature largely focuses on impacts on these forest ecosystems, even though most wind project development has not occurred in such landscapes. The construction of wind energy facilities in largely undisturbed forests may lead to habitat fragmentation for some species. Some species living a minimum distance from the forest edge, for example, may lose habitat due to the so called depth-of-edge influence (NRC, 2007). On the other hand, habitat for other species may actually increase with the increasing amount of edge (NRC, 2007). Research is also being conducted on the possible impacts of wind projects on grassland species. For example, research has been initiated in the United States to investigate the impacts of habitat fragmentation on prairie chickens. In addition, a multi-stakeholder collaborative is being formed to support research on potential habitat impacts to sage grouse in the Pacific Northwest sage brush habitat. Because ecosystem impacts are highly site specific, they are often addressed in the project permitting process (NRC, 2007). Concerns for ecological impacts have also led to ordinances in some countries prohibiting the construction of wind facilities in ecologically sensitive areas.

The impacts of wind projects on marine life have moved into focus as wind energy developments start to go off-shore and, as part of the licensing procedures for off-shore wind projects, numerous studies on possible impacts on marine life and ecosystems have been conducted. As Michel *et al.* (2007) point out, there are ‘several excellent reviews [...] on the potential impacts of offshore wind parks on marine resources; most are based on environmental impact assessments and monitoring programs of existing offshore wind parks in Europe […]’. The impacts of off-shore wind energy development depend greatly on site-specific conditions, and can be both negative as well as positive (Michel *et al.*, 2007; Punt et al., 2009; Wilson and Elliot, 2009). Potential negative impacts involve underwater sounds, electromagnetic fields, and physical disruption. On the other hand, the physical structures may create new breeding grounds or shelters like artificial reefs. From existing studies no final conclusions can be drawn on the impacts of off-shore wind parks in general as the time spans covered and the numbers of wind projects studied are insufficient for such conclusions. In some countries, however, concerns about the impacts of off-shore wind projects on marine life and migrating bird populations have led to national off-shore zoning efforts that exclude the most-sensitive areas from development.

7.6.2.3 Impact of wind project development on the local climate

The possible impact of wind projects on the local climate has also been the focus of some research. Wind projects extract momentum from the air flow and thus reduce the wind speed behind the turbines, and also increase vertical mixing by introducing turbulence across a range of length scales (Petersen *et al.,* 1998). These two processes are described by the term “wind turbine wake” (Barthelmie *et al.,* 2004). Though intuitively turbine wakes must increase vertical mixing of the near-surface layer, and thus may increase atmosphere-surface exchange of heat, water vapour, and other parameters, the magnitude of the effect remains uncertain. Some studies have sought to quantify the effect by treating large wind projects as a block of enhanced surface roughness length or an elevated momentum sink in regional and global models. These studies have found changes in local surface temperature of up to 1°C, and in surface winds of several meters per second (Keith *et al.,* 2004; Kirk-Davidoff and Keith, 2008). Such effects could have both ecological and human impacts. However, the numerical simulations used may not be an ideal analogy for the actual mechanism by which wind turbines interact with the atmosphere. These approaches assume (incorrectly) that the turbines act as an invariant momentum sink; that turbine densities are above what is the norm; and that wind energy development occurs at a more substantial and geographically concentrated scale than is really the case. The results must therefore be viewed with caution.

Observed data and models indicate that large off-shore wind projects may be of sufficient scale to perceptibly interact with the entire (relatively shallow) atmospheric boundary layer (Frandsen *et al.,* 2006), but on-site measurements and remotely sensed near-surface wind speeds suggest that wake effects from large projects are no longer discernible in near-surface wind speeds and turbulence intensity at approximately 20 km downstream (Christiansen and Hasager, 2005; Christiansen and Hasager, 2006; Frandsen *et al.*, 2009). More generally, it should also be recognized that wind turbines are not the only structures to potentially impact local climate variables, and that any impacts caused by increased wind energy development should be placed in the context of other anthropogenic climate influences, as well as the GHG reduction benefits of wind energy.

7.6.3 Impacts on humans

In addition to ecological impacts, wind project development impacts humans in various ways. The primary impacts addressed here include land and marine usage, visual impacts, proximal impacts such as noise, flicker, health, and safety, and property value impacts.

7.6.3.1 Land and marine usage

Wind turbines are sizable structures, and wind projects can encompass a large area (5 MW per km^2 is often assumed), thereby using space that might otherwise be used for other purposes. The land footprint specifically disturbed by on-shore wind turbines and their supporting roads and infrastructure, however, typically ranges from 2% to 5% of the total area encompassed by a project, allowing agriculture, ranching, and certain other activities to continue within the project area. Some forms of land use may be precluded from the project area, such as housing developments, airport approaches, and some radar installations. Nature reserves and historical and/or sacred sites are also often particularly sensitive. Somewhat similar issues apply for off-shore wind.

The impacts of wind projects on aviation, shipping, communications, and radar must also be considered, and depend on the placement of wind projects and wind turbines. Where airplane landing corridors and shipping routes are avoided, interference of wind projects with shipping and aviation can be kept to a minimum (Hohmeyer *et al.*, 2005). Integrated marine spatial planning (MSP) and integrated coastal zone management (ICZM) approaches are also starting to include off-shore wind energy, thereby helping to assess the ecological impacts and economic and social benefits for coastal regions (e.g., Murawsky, 2007; Ehler and Douvere, 2009; Kannen and Burkhard, 2009). Electromagnetic interference (EMI) associated with wind turbines can come in various forms. In general, wind turbines can interfere with detection of signals through reflection and blockage of electromagnetic waves including Doppler produced by the rotation of turbine blades. Many EMI effects can be avoided by not placing wind projects in close proximity to transmitters or receivers (Hohmeyer *et al.*, 2005). Moreover, in the case of military (or civilian) radar, reports have concluded that radar systems can be modified to ensure that aircraft safety and national defence are maintained in the presence of wind energy facilities (BWEA, 2003; Butler and Johnson, 2003; Brenner *et al.*, 2008), though there is a cost to such modifications.

7.6.3.2 Visual impacts

To capture the strongest and most consistent winds, wind turbines are often sited at high elevations and where there are few obstructions, relative to the surrounding area. In addition, wind turbines have consistently grown in hub height and blade swept area. Moreover, as wind energy installations have increased in number and geographic spread, projects located in a wider diversity of landscapes (and seascapes) – including more highly valued landscapes – have begun to be explored. Taken together, these factors often elevate visual impacts to one of the top concerns of communities considering wind energy facilities (Firestone and Kempton, 2007; NRC, 2007; Wolsink, 2007; Wustenhagen et al., 2007; Firestone et al., 2009; Jones and Eiser, 2009), of those living near existing wind facilities (Thayer and Hansen, 1988; Krohn and Damborg, 1999; Braunholtz and Scotland, 2003; Warren et al., 2005), and of institutions responsible for overseeing wind energy development (Nadaï and Labussiere, 2009). As a result, some contend that a thorough rethinking of what a “landscape” means – and therefore what should be protected – is required (Pasqualetti et al., 2002; Nadaï and Labussiere, 2009).

7.6.3.3 Noise, flicker, health, and safety

A variety of proximal “nuisance” effects are also sometimes raised with respect to wind development. Noise from wind turbines can be a problem, either for those within a very close range of a typical turbine or farther away when turbines are not well designed or maintained. Typically, the sound level of a modern wind turbine at the tip of the rotor blade is around 100 dB at a distance of one meter, depending on the type of turbine and the wind speed at which the sound is measured (Hohmeyer *et al.*, 2005). Directly under the turbine the noise level is reduced to about 70 dB due to the vertical distance to the tip of the rotor blades; though 100 dB is equivalent to the noise of a steam hammer, 70 dB is equivalent to the noise of a roadway at a distance of about 30 meters. Noise effects diminish with distance (roughly a 6 dB reduction with each doubling of the distance from the source), and a sound pressure level of 35-45 dB can be reached with modern wind turbines at a distance of roughly 350 meters (EWEA, 2009); this is the level of a person speaking with a normal voice at a distance of one meter. Rotating turbine blades can also cast moving shadows, which may be annoying to residents living close to wind turbines. Turbines can be sited to minimize these concerns, or the operation of wind turbines can be stopped during acute periods (Hohmeyer *et al.*, 2005), and in some countries the use of such operation control systems is mandated by licensing authorities. As discussed above, EMI impacts can take many forms, including impacts on TV, GPS, and communications systems. Where these impacts do exist, they can be managed by appropriate siting of wind projects and through other technical solutions. Finally, although wind turbines can shed parts of blades, or in exceptional circumstances whole blades, as a result of an accident or icing (or more, broadly, shed ice that has built up on the blades, or collapse entirely), to 2001 there had been no cases of people being injured as a result of such incidents (DTI, 2001).

7.6.3.4 Property values

The aesthetic concerns discussed above, real or perceived, may translate into negative impacts on residential property values at the local level. Further, if various proximal nuisance effects are prominent, such as turbine noise, shadow flicker, health, or safety concerns, additional impacts to local property values may occur. Although these concerns may be reasonable given effects found for other environmental disamenities (e.g., high voltage transmission lines, fossil fuel power plants, and landfills; see Simons, 2006), published research has not found strong evidence of an effect for wind energy facilities (e.g., Sims and Dent, 2007; Sims et al., 2008; Hoen et al., 2009). This might be explained by the setbacks normally employed between homes and wind turbines; studies on the impacts of transmission lines on property values, for example, often find that effects can fade at distances of 100m (Kroll and Priestley, 1992; Des Rosiers, 2002). Alternatively, any effects may be too infrequent and/or small to distinguish statistically. More research is needed on the subject, but based on other disamenity research (e.g. Kroll and Priestley, 1992; Boyle and Kiel, 2001; Jackson, 2001; Simons and Saginor, 2006), if any impacts do exist, it is likely that those effects are most pronounced within short distances of wind turbines, in the period immediately following announcement, but fade over distance and time after a wind energy facility is constructed.

7.6.4 Public attitudes and acceptance

Despite the possible impacts described above, surveys have consistently found wind energy to be widely accepted by the general public (e.g., Warren *et al.*, 2005). That said, translating this broad support into increased deployment (closing the "social gap" – see e.g., Bell *et al.*, 2005) often requires the support of local host communities and/or decision makers. To that end, a number of concerns exist that might temper the enthusiasm of these stakeholders, such as visual, proximal, or property value impacts (Jones and Eiser, 2009). In general, research has found that public concern is greater after the announcement of a wind energy facility but before construction, but that acceptance increases after construction when actual risks can be quantified (Wolsink, 1989; Braunholtz and MORI Scotland, 2003; Warren *et al.*, 2005; Eltham *et al.*, 2008). Additionally, those most familiar with existing wind facilities, including those who live closest to them, have sometimes been found to be more accepting (or less concerned) than those further away (Krohn and Damborg, 1999; Warren *et al.*, 2005), though this support paradigm has sometimes been found to break down at very close distances (Kabes and Smith, 2001) and when turbines are sitting idle

(Thayer and Freeman, 1987). A number of authors have found that a lack of support before the facility is erected can alter perceptions later. For example, those opposed to wind facilities found those facilities to be considerably noisier and more visually intrusive that those in favour of the same facilities (Krohn and Damborg, 1999; Jones and Eiser, 2009). Additionally, some research has found that concerns can be compounding. For instance, those who found turbines to be visually intrusive found their noise to be more annoying (Pedersen and Waye, 2004). In many cases, it is likely that "beauty is in the eye of the beholder" (Warren *et al.*, 2005, p. 14), as aesthetic perceptions have been found to be the strongest single influence for support and opposition of wind development (Pasqualetti *et al.*, 2002; Warren *et al.*, 2005; Wolsink, 2007).

7.6.5 Minimizing social and environmental concerns

Regardless of what type and degree the local concerns are, and how they are tempered, addressing them directly is an essential part of any successful siting process. This might, for example, include conducting ecological impact studies, performing visual simulations of alternative facility designs, and establishing wide set-back requirements. Similarly, involving the community in the siting process will likely improve outcomes. Public attitudes have been found to improve when the development process is perceived as being transparent and involving public comment (Wolsink, 2000; McLaren Loring, 2006; Gross, 2007), especially when community involvement begins before a final facility location is chosen (Nadaï and Labussiere, 2009). Further, experience in Europe suggests that increased community involvement in and even ownership of local wind projects can improve public attitudes towards wind development (Gross, 2007; Wolsink, 2007; Jones and Eiser, 2009). Finally, broader concepts, such as the rethinking of "landscape" to incorporate wind turbines will continue to be of use (e.g., Wustenhagen et al., 2007; Nadaï and Labussiere, 2009).

Proper planning for both on-shore and off-shore wind can also help to minimize social and environmental impacts, and a number of siting guideline documents have been developed (Minister für Soziales, Gesundheit und Energie, 1995; Nielsen 1996; NRC, 2007; AWEA, 2008). The appropriate siting of wind turbines can minimize the impact of noise, flicker, and electromagnetic interference. Appropriate siting will generally avoid placing wind turbines too close to dwellings, streets, railroad lines, and airports, and will avoid areas of heavy bird and bat activity. Habitat fragmentation caused by access roads and power lines can often be minimized by careful placement of wind turbines and facilities, and by proactive governmental planning for wind deployment. Examples of such planning can be found in many jurisdictions across the world, both for on-shore and for off-shore wind.

Even if the environmental impacts of wind energy are minimized through proper planning procedures and community involvement, some impacts will remain. Although an all-encompassing numerical comparison of the full external costs and benefits of wind energy is impossible, as some impacts are very difficult to monetize, available evidence makes it clear that the positive environmental and social effects of wind energy generally outweigh any negative impacts that remain after careful planning and siting procedures are followed (see, e.g., Jacobson, 2009).

7.7 Prospects for technology improvement and innovation

Over the past three decades, innovation in the design of utility-scale wind turbines has led to significant cost reductions, while the capacity of individual turbines has grown markedly. The "square-cube law"[16] suggests a natural "size limit" for wind turbines. To date, engineers have

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[16] The "square-cube law" states that as a wind turbine increases in size, its theoretical energy output tends to increase by the square of the rotor diameter (i.e., the rotor-swept area), while the volume of material (and therefore its mass and cost) increases as the cube of the rotor diameter, all else being equal [TSU: sentence unclear]. As a result, at some size, the cost of a larger turbine will grow faster than the resulting energy output and revenue, making further scaling uneconomic.

successfully engineered around this relationship by changing design rules with increasing turbine size and by removing material or using it more efficiently to trim weight and cost. Engineering around the "square-cube law" remains the fundamental objective of research efforts aimed at further reducing the delivered cost of energy from wind turbines, especially for off-shore installations.

This section describes research and development programs in wind energy (7.7.1), system-level design and optimization approaches that may yield further cost reductions in wind-generated electricity (7.7.2), component-level opportunities for innovation in wind technology (7.7.3), and opportunities to improve the scientific underpinnings of wind technology (7.7.4). Significant opportunities remain for design optimization of on-shore and off-shore wind turbines, and sizable cost reductions remain possible in the years ahead, though improvements are likely to be more-incremental in nature than radical changes in fundamental design.[17]

7.7.1 Research and development programs

Public and private research and development (R&D) programmes have played a major role in the technical advances seen in wind energy over the last decades (Klaassen *et al.*, 2005; Lemming *et al.*, 2009). Government support for R&D, in collaboration with industry, has led to system and component-level technology advancements, as well as improvements in resource assessment, technical standards, grid integration, wind production forecasting, and other areas. From 1974 to 2006, government R&D budgets for wind energy in IEA countries totalled $3.8 billion (2005$): this represents an estimated 10% share of RE R&D budgets, and just 1% of total energy R&D expenditures (IEA, 2008; EWEA, 2009). In 2008, OECD research funding for wind energy totalled $200 million (2008$), or 1.5% of all energy R&D funding. Government-sponsored R&D programs have often emphasized longer-term innovation, while industry-funded R&D has focusing on shorter-term production, operation, and installation issues. Though data are scarce on industry R&D funding, EWEA (2009) and Carbon Trust (2008a) find that the ratio of turbine manufacturer R&D expenditures to net revenue typically ranges from 2% to 3%.

Wind energy research strategies have been developed through government and industry collaborations in the U.S. and in Europe. In a study to explore the technical and economic feasibility of meeting 20% of electricity demand in the U.S. with wind energy, the U.S. Department of Energy found that key areas of further research included continued development of turbine technology, improved and expanded manufacturing processes, gird integration of wind energy, and siting and environmental concerns (U.S. DOE, 2008). The European Wind Energy Technology Platform (TPWind) similarly describes a long series of research and development targets (E.U., 2008). One notable feature of both of these planning efforts is that neither envisions a sizable technology breakthrough for wind energy in the years ahead: instead, the path forward is seen as many evolutionary steps, executed through incremental technology advances, that may cumulatively bring about a 30% to 40% improvement in the delivered cost of wind energy over the next two decades.

7.7.2 System-level design and optimization

Modern wind turbine design and operation requires advanced, integrated design approaches to optimize system cost and performance. Many studies of advanced wind turbine concepts have identified a number of areas where technology advances could result in changes to the capital cost, annual energy production, reliability, O&M, and grid integration of wind energy. Scaling studies

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[17] This section focuses on scientific and engineering challenges directly associated with reducing the cost of wind energy, but additional research areas of importance include: research on the integration of wind energy into utility systems and grid compatibility (e.g., forecasting, storage, power electronics); social science research on policy measures and social acceptance; and scientific research to understand the impacts of wind energy on the environment and on humans.

exploring the system-level impacts of advanced concepts were conducted by the U.S. DOE under the Wind Partnership for Advanced Component Technologies (WindPACT) project (GEC, 2001; Griffin, 2001; Shafer et al., 2001; Smith, 2001; Malcolm and Hansen, 2006), including a number of additional detailed component-level studies. Ultimately, component-level advances are evaluated based on system-level cost and performance impacts; to be viable, increased energy capture associated with larger rotors, for example, must increase expected electricity sales revenue to a greater extent than the additional cost of material as well as impacts on installation costs associated with larger cranes. Sophisticated design approaches are required to systematically evaluate advanced wind turbine concepts.

The U.S. DOE (2008) report summarizes the range of potential impacts on energy production and capital costs from a number of these advances; these ranges are shown in Table 7.4. Though not all of these potential improvements may be achieved, there is sufficient potential to warrant continued research and development. The most likely scenario, as shown in Table 7.4, is a sizeable increase in energy production with a modest drop in capital cost (compared to 2002 levels, which are the baseline for the estimates in Table 7.4).

Table 7.4. Areas of potential technology improvement from a 2002 baseline wind turbine (U.S. DOE 2008)*

		Increments from Baseline (Best/Expected/Least, Percent)	
Technical Area	**Potential Advances**	**Annual Energy Production (%)**	**Turbine Capital Cost (%)**
Advanced Tower Concepts	* Taller towers in difficult locations * New materials and/or processes * Advanced structures/foundations * Self-erecting, initial or for service	+11/+11/+11	+8/+12/+20
Advanced (Enlarged) Rotors	* Advanced materials * Improved structural-aero design * Active controls * Passive controls * Higher tip speed/lower acoustics	+35/+25/+10	-6/-3/+3
Reduced Energy Losses and Improved Availability	* Reduced blade soiling losses * Damage tolerant sensors * Robust control systems * Prognostic maintenance	+7/+5/0	0/0/0
Advanced Drive Trains (Gearboxes and Generators and Power Electronics)	* Fewer gear stages or direct drive * Medium/low-speed generators * Distributed gearbox topologies * Permanent-magnet generators * Medium-voltage equipment * Advanced gear tooth profiles * New circuit topologies * New semiconductor devices * New materials (GaAs, SiC)	+8/+4/0	-11/-6/+1
Manufacturing Learning	* Sustained, incremental design and process improvements * Large-scale manufacturing * Reduced design loads	0/0/0	-27/-13/-3
Totals		+61/+45/+21	-36/-10/+21

The baseline for these estimates was a 2002 turbine system in the U.S. There have already been sizeable improvements in capacity factor since 2002, from just over 30% to almost 35%, while capital costs have increased due to large *increases in commodity costs in conjunction with a drop in the value of the U.S. dollar. Therefore, working from a 2008 baseline, one might expect a more-modest increase in capacity factor, but the 10% capital cost reduction is still quite possible (if not conservative), particularly from the higher 2008 starting point. Finally, the table does not consider any changes in the overall wind turbine design concept (e.g., 2-bladed turbines).*

The European Wind Energy Technology Platform has also developed a roadmap that is being discussed with E.U. member countries (E.U., 2008; E.C., 2009). The roadmap (Figure 7.19) is expected to form the basis for the future development of European wind energy research and development strategies, with the following areas of focus: new turbines and components; off-shore structures; grid integration; and wind resource assessment and spatial planning.

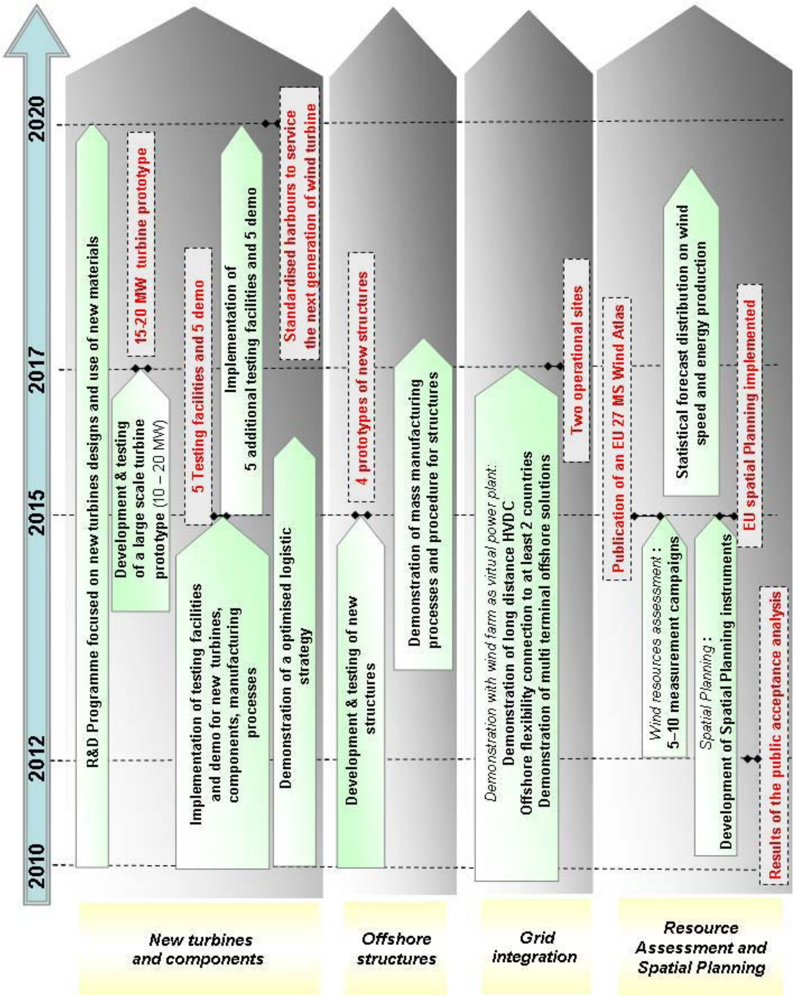


Figure 7.19. European wind initiative R&D roadmap (E.C., 2009).

7.7.3 Component-level innovation opportunities

The potential areas of innovation outlined in Table 7.4 deserve further description, as do two additional topics: advanced turbine concepts and off-shore technology advancement.

7.7.3.1 Advanced tower concepts

Taller towers allow the rotor to access higher wind speeds in a given location, increasing annual energy capture; however, the cost of large cranes and transportation acts as a limit to tower height. As a result, research is being conducted into several novel tower designs that would eliminate the need for cranes for very high, heavy lifts. One concept is the telescoping or self-erecting tower, while other designs include lifting dollies or tower-climbing cranes that use tower-mounted tracks to lift the nacelle and rotor to the top of the tower. Still other developments aim to increase the height of the tower without unduly sacrificing material demands through the use of different materials, such as concrete and fibreglass, or different designs, such as space-frame construction or panel sections. (For more information, see GEC, 2001; Malcolm, 2004; Lanier, 2005; and Native American Technologies, 2006).

7.7.3.2 Advanced rotors and blades

In recent years, blade mass has been scaling at roughly an exponent of 2.4 to rotor diameter, compared to the expected exponent of 3.0 based on the "square-cube" law (Griffin, 2004). The significance of this development is that wind turbine blades have become lighter for a given length over time (Figure 7.20).

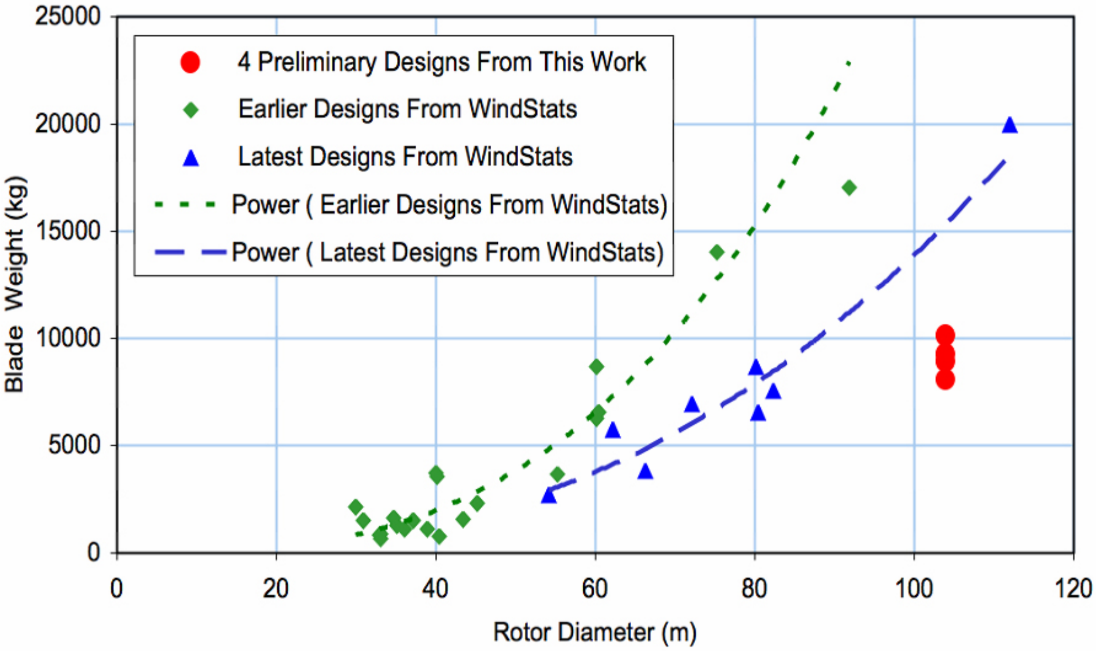


Figure 7.20. Reduced growth in blade weight due to the introduction of new technology (T.P.I. Composites, 2004).

If advanced R&D can provide even better blade design methods, coupled with better materials, such as carbon fibre composites, and advanced manufacturing methods, then it will be possible to continue to innovate around the square-cube law in blade design. A simple approach to reducing cost involves developing new blade airfoil shapes that are much thicker where the blade needs the most support, producing inherently better structural properties, while allowing less material to be used in other segments of the blade. To date these thicker airfoil shapes in the blade root area have sacrificed too much aerodynamic performance. Another approach to increasing blade length while limiting increased material demand is to reduce the fatigue loading on the blade. The benefit of this approach is that the approximate rule of thumb for fibreglass blades is that a 10% reduction in cyclic stress can more than double the fatigue lifetime. Blade fatigue loads can be reduced by controlling the blade's aerodynamic response to turbulent wind by using mechanisms that vary the angle of attack of the blade airfoil relative to the wind inflow. This is primarily accomplished with full-span blade pitch control. An elegant concept, however, is to build passive means of reducing loads directly into the blade structure (Ashwill, 2009). By carefully tailoring the structural properties of the blade using the unique attributes of composite materials, the blade can be built in a way that couples the bending deformation of the blade resulting from the wind with twisting deformation which passively mimics the motion of blade pitch control. Another approach is to build the blade in a curved shape so that the aerodynamic load fluctuations apply a twisting movement to the blade, which will vary the angle of attack (Ashwill, 2009). Because wind inflow displays a complex variation of speed and character across the rotor disk, partial blade span actuation and sensing strategies to maximize load reduction are also promising (Buhl *et al*, 2005; Buhl *et al*, 2007; Lackner and van Kuik, 2009). Devices such as trailing edge flaps and micro-tabs are being investigated, but new sensors may need to be developed with a goal of creating “smart” blades with embedded sensors and actuators to control local aerodynamic effects (Andersen *et al*., 2006; Berg *et al.,* 2009). Basic understanding and mathematical modelling of wind turbine aeroelastic (Section 7.7.4.1), aerodynamic (Section 7.7.4.2), and aeroacoustic (Section 7.7.4.3) responses that are associated with such complicated blade motion, as well as control algorithms to incorporate these sensors and actuators in wind turbine operation schemes (Section 7.7.4.4), must be developed to achieve these new designs. Several of these innovative concepts are being developed in U.S. and European research projects, in conjunction with industry, raising the possibility of significant reductions in fatigue loads on the blades.

Concepts such as on-site manufacturing and segmented blades are also being explored to help reduce transportation costs. In UpWind, for example, one of the goals is to develop a segmented blade. Some manufacturers, meanwhile, are investigating production methods that would enable segmented moulds to be moved into temporary buildings close to the site of major wind installations so that the blades can be made close to or at the wind project site.

7.7.3.3 Reduced energy losses and improved availability

Advanced turbine control and condition monitoring are expected to provide a primary means to improve turbine reliability and availability, reduce O&M costs, and ultimately increase energy capture. Advanced controllers are envisioned to be able to control the turbine through turbulent winds, monitor and adapt to the wind conditions, and anticipate and protect against damaging wind gusts. Condition-monitoring systems of the future are expected to track and monitor ongoing conditions at critical locations in the turbine system and report incipient failure possibilities and damage evolution, so that outages and downtime can be minimized. For example, advanced fibre optic sensors can continually and reliably measure blade strains and damage accumulation, although it should be noted that greater uniformity of the quality of blade manufacturing is required to make the application of such techniques effective. Other sensors can monitor the chemical and particulate conditions in the gearbox lubricant, while accelerometers measure vibration and shock loads in the drive train and on other key structural components. By tracking wind conditions and power output, the blade pitch can be adjusted to maximize energy output, even when the blades are soiled. The development and evolution of advanced control and monitoring systems of this nature will take years of operational experience, and optimization algorithms will likely be turbine-specific; the general approach, however, will be transferrable between turbine designs and configurations.

7.7.3.4 Advanced drive trains, generators, and power electronics

Several unique designs are under development to reduce drive train weight and cost while improving reliability (Poore and Lettenmeier, 2003; Bywaters *et al*., 2004; EWEA, 2009), including the use of direct-drive generators (removing the need for a gearbox). The trade-off is that the slowly rotating generator must have a high pole count and be large in diameter, imposing a weight penalty. The decrease in cost and increase in availability of rare-earth permanent magnets is expected to significantly affect the size and cost of future direct-drive generator designs. Permanent-magnet designs tend to be more compact and potentially lightweight and reduce electrical losses in the windings.

A hybrid of the direct-drive approach that offers promise for future large-scale designs is the single-stage drive using a low- or medium-speed generator. This allows the use of a generator that is significantly smaller and lighter than a comparable direct-drive design. Another approach that offers promise is the distributed drive train, where rotor torque is distributed to multiple smaller generators, reducing overall size and weight (Clipper Wind Technology, 2003).

Power electronics that provide full power conversion from variable frequency AC electricity to constant frequency 50 or 60 Hz are also capable of providing ancillary grid services. The growth in turbine size and the corresponding increased power output is helping to spur interest in larger power electronic component ratings, as well as innovative higher-voltage circuit topologies. In the future, it is expected that wind turbines will use medium-voltage generators and converters (Erdman and Behnke, 2005), and make use of new high-voltage and higher-capacity circuits and transistors.

7.7.3.5 Manufacturing and learning curve

Manufacturing learning refers to the learning by doing achieved in serial production lines with repetitive manufacturing (see Section 7.8.4 for a broader discussion of learning in wind technology). Though turbine manufacturers already are beginning to operate at significant scale, as the industry expands further, additional cost savings can be expected. Increased automation and optimized manufacturing processes contribute to cost reductions associated with learning by doing.

7.7.3.6 Advanced turbine concepts

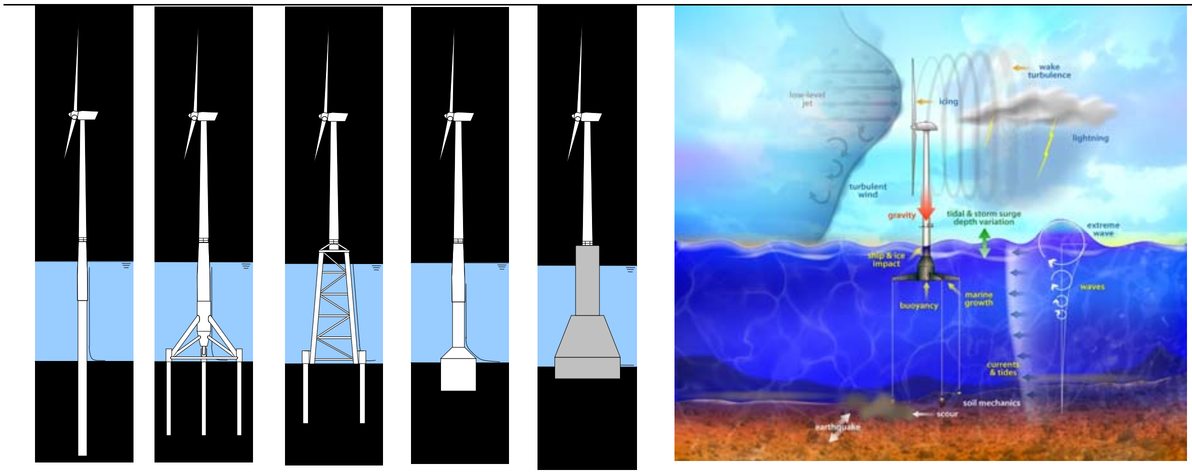
Almost all commercial wind turbines are three-bladed, upwind machines. However, there has been a long-running debate about optimum turbine design and configuration, with early designs including one-, two-, and three-bladed turbines. Some believed that a two-bladed turbine configuration was the minimum cost architecture, particularly for very large turbines of the multi-megawatt class. Nonetheless, a key advantage of the three-bladed turbine, which eventually led to its dominance, is that the dynamic equations of motion are simpler because rotor inertia is symmetric, making the engineering design simpler. In addition, there was very little cost penalty for the three smaller blades of the early turbines, and because the rotor speed was lower they also emitted less noise, as well as having a more pleasing aesthetic during operation.

With current turbine designs operating at lower speeds, and offshore developments being less limited by issues of noise, the advantages of a three-bladed turbine may no longer be valid. In addition, the state-of-the-art in low-noise airfoils has advanced such that targeted R&D may reduce the previous noise penalty for one- and two-bladed turbine designs. As a result, two-bladed downwind wind turbines are being investigated off-shore applications. However, the large existing wind turbine manufacturers hesitate to develop alternative designs, due to the high degree of risk involved in shifting away from longstanding design concepts combined with a long and expensive path to commercialization. As a result, significantly different off-shore turbine designs are unlikely to be commercialized before 2020 (Carbon Trust, 2008a).

7.7.3.7 Off-shore research and development opportunities

The larger, lighter, more-flexible turbines envisioned for off-shore applications, perhaps 10 MW in size or even larger, can benefit from many of the advances described previously. The development of large turbines for off-shore applications remains a significant research challenge, however, that requires continued advancement in component design and system-level analysis. Concepts that reduce the weight of the blades, tower, and nacelle become more important as size increases, providing opportunities for greater advancement than may be incorporated in on-shore wind technology.

Additional R&D opportunities exist in foundation design, and foundation structure innovation offers the potential to access deeper waters, thereby increasing the potential wind resource available. Off-shore turbines have historically been installed on a mono-pile structure that is essentially an extension of the tower and is appropriate in relatively shallow water under 30 m in depth. To more cost-effectively access deeper water locations, concepts with space-frame structures or tension-leg mooring designs, as well as floating wind turbines, are under exploration and development. Floating wind turbines and floating platforms, in particular, increase the complexity of turbine design due to the additional motion of the base, but can – if cost-effective – offer access to significant additional wind resource potential, though the cost of off-shore transmission infrastructure will be a deterrent to moving too far from shore. Figure 7.21(a, b) depicts some of the foundation concepts (a) being employed or considered in the near term, while also (b) illustrating the concept of floating wind turbines, which are being considered for deeper-water applications in the longer term.



(a) Near-term off-shore foundation concepts

(b) Floating off-shore turbine concept

Source: UpWind.eu

Source: National Renewable Energy Laboratory

Figure 7.21(a,b). Off-shore wind turbine foundation designs

High waves and strong winds can make accessing off-shore wind turbines difficult. This challenge, coupled with slow transport time from land and the relatively low reliability of early off-shore turbines, are some of the factors that make off-shore wind energy more expensive than on-shore projects. In an effort to decrease this cost differential, additional research is expected to be focused on achieving higher reliability, fewer scheduled and unscheduled O&M visits, and higher availability than off-shore turbine models deployed thus far have experienced.

Advancements in off-shore installation and manufacturing techniques are also possible, in part learning from the off-shore oil and gas industries. For example, off-shore wind turbines could be constructed and assembled in or near seaport facilities, thereby eliminating the need to ship large components over roadways. Off-shore turbines could also be designed such that installation of those turbines consists of floating the assembled turbines to their final locations, and therefore erecting the structures with minimal off-shore crane requirements.

7.7.4 The Importance of underpinning science

Wind turbines operate in a challenging environment, and are designed to withstand a wide range of conditions with minimal attendance. Wind turbines are complex, nonlinear, dynamic systems forced by gravity, centrifugal, inertia, and gyroscopic loads as well as unsteady aerodynamic, hydrodynamic (for off-shore), and corrosion impacts. Research in a number of areas of fundamental science will improve the physical understanding of this operating environment, which in turn can lead to more-precise design requirements. To develop the innovative components described in Section 7.7.3, the reliability and accuracy of the mathematical and experimental basis underlying turbine design methodologies becomes more critical. Research in areas of aeroelastics, unsteady aerodynamics, aeroacoustics, advanced control systems, materials science, and atmospheric science has yielded improved design capabilities in the past and can continue to improve mathematical models and experimental data that reduce the risk of unanticipated failures, increase the reliability of the technology, and encourage innovation of wind turbine and wind project design.

7.7.4.1 Aeroelastics

The wind industry relies extensively on the use of comprehensive dynamics models for wind turbine performance, loads, and stability analyses.[18] The integrated modelling of these physical phenomena is important for design optimization (Quarton, 1998; Rasmussen *et al.*, 2003). The minimum features required of the aeroelastic tools and experimental verification when applied in the design process are dictated by international wind turbine design and safety standards. The design process illustrated in Figure 7.8(a) requires an accurate prediction of extreme and fatigue loads over a range of operational conditions, including normal operation, start/stop sequences, and parked/idling conditions (IEC, 2005; IEC, 2008c). Limitations and consequent inaccuracies in the aeroelastic tools and the experimental verification of those tools limit advancements of wind turbine technology, and overcoming these limitations is critical to the successful long-term improvement of performance, operation, and reliability of wind turbines.

Overcoming the existing limitations of these tools and experimental verification methods becomes even more important as turbines grow in size, incorporate novel load control technologies together with more-advanced condition monitoring systems, and are installed off-shore. For example, as turbines grow in size and are optimized, the structural flexibility of the turbines will increase, causing more of the turbine's vibration frequencies to play a prominent role in the system's response. To account for these effects, future aeroelastic tools will have to better model large variations in the wind inflow across the rotor, higher-order vibration modes, nonlinear blade deflection, and aeroelastic damping and instability (Quarton, 1998; Rasmussen *et al.*, 2003; Riziotis *et al.*, 2004; Hansen, 2007). Future aeroelastic tools may also need to incorporate higher fidelity drive train dynamics models, including detailed models of gears, shafts, and bearings, to properly account for the couplings between the drive train and rotor (Peeters *et al.*, 2006; Heege *et al.*, 2007). The application of novel load-mitigation control technologies, such as can be applied to blades, or advanced sensors and embedded actuators for active control (e.g., deformable trailing edges), will require analysis based on aeroelastic tools that are adapted for these architectures (Buhl *et al.*, 2005; GEC, 2005). Off-shore wind applications will require that aeroelastic tools better model the coupled dynamic response of the wind turbine and the foundation / support platform, as subjected to combined wind and wave loads. The modelling capabilities required will depend on the type of off-shore foundation (Passon and Kühn, 2005; Jonkman, 2007). Analysis of downwind two-bladed rotors, which may ultimately become more-prevalent off-shore, will benefit from improved downwind tower wake models (Butterfield *et al.*, 2007; Zahle *et al.*, 2009).

Because aerodynamic models are the least-accurate component of aeroelastic tools, improving them will produce the greatest benefit. Currently, aerodynamic models rely upon Blade-Element Momentum (BEM) methods (Spera, 2009) to calculate the aerodynamic forces along the span of the

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[18] The fundamental models are comprehensive "aero-hydro-servo-elastic" tools (herein, "aeroelastic tools"), meaning that they incorporate integrated models for aerodynamic loads, hydrodynamic loads (for off-shore systems), control system (servo) behavior, and structural-dynamic (elastic) loads (e.g., gravitational, inertial, centrifugal, and gyroscopic loads) (see Figure 7.21 (b)).

blade; these methods provide computational efficiency but also result in a simplistic representation of the blade aerodynamics. Model improvements include developing improved corrections to these (BEM)-based models and replacing BEM-based models with higher fidelity models such as prescribed and free wake models or three-dimensional Computational Fluid Dynamics (CFD) models (Snel, 1998; Snel, 2003), as described in Section 7.7.4.2 below. More research should also be directed towards the rotor wakes' influence on the aeroelastic response of turbines in wind project arrays (Larsen *et al.*, 2008). Finally, the accuracy of design calculations will be improved with verification (model-to-model) (Simms *et al.*, 2001) and validation (model-to-wind-tunnel experiments and full-scale field tests) of the aeroelastic tools (Schepers *et al.*, 2002; Schreck, 2002). As aeroelastic tools are upgraded, they must be further verified and experimentally validated to ensure their accuracy.

7.7.4.2 Aerodynamics

As wind energy gained momentum in the early 1980s, turbine aerodynamics emerged as a central research issue. To address energy capture shortfalls and establish a threshold capability for load predictions, initial work concentrated on steady, two-dimensional blade flow fields. This effort produced airfoil (blade) designs optimized for wind turbine applications and enabled significantly increased energy capture (Tangler and Somers, 1995; Timmer and van Rooij, 2003; Fuglsang *et al.*, 2004). At the same time, basic BEM-based design codes were developed, which facilitated early wind turbine designs (Spera, 2009).

Comparisons between wind tunnel and rotating blade data implied that three-dimensional effects figured prominently in rotating blade flow fields (Butterfield, 1989; Madsen and Rasmussen, 1994; Madsen *et al.*, 2010). The underlying cause was later identified as rotational augmentation, which has now been quantified in detail (Schreck and Robinson, 2003) and found to be significantly unsteady (Schreck, 2007). Analytically based rotational augmentation models have been formulated to include this effect in BEM codes (e.g., Eggers and Digumarthi, 1992; Snel *et al.,* 1992; Du and Selig, 1998). In addition, early rotating blade measurements for yawed rotor operation revealed prominent load oscillations linked to dynamic stall (Butterfield, 1989), which later was characterized for a broad range of operating conditions (Schreck *et al.*, 2000, 2001). Various empirical models for dynamic stall that were originally constructed for rotorcraft applications have been adapted for wind turbine BEM codes (e.g., Bierbooms, 1992; Yeznasni *et al*, 1992), with the Leishman-Beddoes model (Leishman, 2006) most widely employed. As turbines become larger and more flexible, these unsteady effects become more important and improved unsteady aerodynamic models will be required; this will require a combination of fundamental and experimental research.

As blade-flow field modelling complexity has grown, so too has wake model sophistication. The equilibrium wake inherent in basic BEM models lacked fidelity under time-varying inflow conditions, and so was replaced with analytically based dynamic wake representations of low order (Pitt and Peters, 1981; Suzuki and Hansen, 1998) and then of higher order (Peters *et al.*, 1989; Suzuki and Hansen, 1999). Characterization of the wake itself and resulting accuracy enhancements can be realized at the cost of increased computational intensiveness with prescribed and free wake models (Snel and Schepers, 1992). BEM models augmented with analytically and empirically based models as summarized above remain the industry standard for much of wind turbine design. However, the first principles nature of high-performance CFD codes and the prospects for greater predictive accuracy is prompting broader application (Hansen *et al.*, 2006). As turbine aerodynamics modelling advances, the crucial role (e.g., Simms *et al.*, 2001) of research-grade turbine aerodynamics experiments (Hand *et al.*, 2001; Snel and Schepers, 2009) grows ever more evident, as does the need for future high-quality laboratory and field experiments. Even though wind turbines now extract energy from the flow field at levels approaching the theoretical maximum, improved understanding of aerodynamic phenomena will allow more accurate calculation of loads and thus the development of more precise design criteria and greater certainty of wind turbine power production and reliability.

7.7.4.3 Aeroacoustics

Aeroacoustic noise (i.e., the noise of turbine blades passing through the air) is a limiting factor on the performance of wind turbines, and most turbines' rotational speeds are limited because of noise constraints. With quieter gearbox and generator designs, aeroacoustic noise is now considered the dominant noise source for wind turbine operation (Wagner *et al*., 1996). The physical mechanisms and basic modelling techniques for aeroacoustic noise from wind turbines were identified by Lighthill (1952), Curle (1955), and Ffowcs *et al*. (1969). These have led to semi-empirical methods for airfoil noise prediction that are used in many different industries (e.g., Amiet, 1975; Brooks *et al*., 1989). These semi-empirical methods have been modified and applied to a number of different wind turbine noise prediction codes (Wagner *et al*., 1996; Moriarty and Milgiore, 2003; Zhu et al., 2005). More advanced computational aeroacoustics tools have also been developed (Shen and Sørensen, 2007; Zhu *et al*., 2007) that may see greater use in the future as computational constraints are relaxed.

Measurement of wind turbine noise has traditionally required single microphone techniques (IEC, 1998) to quantify overall sound pressure level and satisfy noise ordinances. In more recent years, acoustic arrays (Oerlemans *et al*., 2007) have been developed to help identify the locations of noise sources. This research has found that, on traditional blade designs, the noisiest part of the wind turbine is the outer 25% of the downward passing blade, with the noise source originating at the trailing edge of the blade (Oerlemans *et al*., 2008).

Reducing aeroacoustic noise can be most easily accomplished by slowing down rotor speed. Noise can be reduced without sacrificing aerodynamic performance by using aeroacoustic airfoil design techniques (Migliore and Oerlemans, 2004; Lutz *et al*., 2007). Often, this process involves changing the airfoil shape to minimize the boundary layer thickness at the airfoil trailing edge. Some initial research has shown small reductions in noise based on tip shape (Wagner *et al*., 1996; Fleig *et al*., 2004), but measurements have been inconclusive (Migliore, 2009). Trailing edge modifications such as serrations (Howe, 1991) have shown promise for noise reduction. Field testing of different mitigation methods shows small reductions from optimally shaped airfoils and larger reductions for trailing edge serrations (Oerlemans *et al*., 2008). In addition to blade shape, upwind rotors – as is now standard – are generally less noisy than downwind designs, because in downwind machines the interaction between the blades and the downwind tower wake create a large impulsive noise source (McNerney *et al*., 2003). Understanding trade-offs in airfoil design for structural efficiency or load mitigation as described in Section 7.3.3 and resulting aeroacoustic noise requires further development of these models and field testing to validate analytic results.

Noise propagation is important, as the condition of the atmosphere (van den Berg, 2008) and the local terrain (Prospathopoulos and Voutsinas, 2005) influence how noise travels to observer locations. Prediction methods for propagation include simple ray tracing (Prospathopoulos and Voutsinas, 2005) and more-complicated methods (Cheng *et al*., 2006).

7.7.4.4 Advanced control concepts

Control systems are critical to wind turbine operation; their goal is to maximize power capture, reduce structural loads, and maintain safe turbine operation. Commercial wind turbines are becoming larger, with lighter, more-flexible components. Designing controls to meet multiple control objectives for these large, dynamically active structures is a major challenge. To date, most commercial turbine controllers are designed using classical control design approaches. These approaches result in numerous single-input single-output control loops, but this approach can destabilize the turbine if not carefully designed. More advanced state-space control methods can meet multiple control objectives in a single control loop to assure stability of the turbine system. Progress in the design of advanced controls includes the implementation of periodic control gains to regulate power production and blade loading (Stol and Balas, 2003). Disturbance accommodating control methods developed by Johnson (1976) also show promise for reducing turbine loads while maintaining power production levels (Wright 2004; Hand and Balas, 2004). Many of these more advanced methods rely upon linear wind turbine models. An alternative control technique is to account for the non-linear behaviour of a wind turbine through adaptive control, in which the control gains “adapt” to changing conditions (Johnson *et al.,* 2004; Johnson and Fingersh 2008; Frost *et al.*, 2009). Continued development of modern control methods that are able to incorporate more-advanced sensor inputs and achieve multiple control objectives will contribute to reduced fatigue loading (see Section 7.7.3.2) and improved energy capture (see Section 7.7.3.3).

Most control algorithms depend on measured turbine signals in the control feedback loop for load mitigation, yet these turbine measurements are often unreliable or too slow. A significant advantage in load mitigating capability might be attained by measuring complex wind phenomena ahead of the turbine and preparing the controls in advance to mitigate the resulting loads. Research by Harris *et al.* (2006) investigated the use of Light Detection and Ranging (LIDAR) and Larsen *et al.* (2004) explored pressure probe measurements ahead of the blade to provide the controller with advanced wind-speed measurements; such approaches show promise for more sophisticated control strategies that allow for greater load reduction.

7.7.4.5 Materials science

Wind turbines are designed to survive at least 20 years, which corresponds to more than one-hundred million load cycles on the blades. Because blades can be stiffness or fatigue driven, material testing is very important to provide designers with an array of candidate blade materials that are fully characterized. Comprehensive databases are maintained to characterize these materials (Mandell and Samborsky, 1997; Brøndsted *et al*., 2005; Brøndsted *et al*., 2008; Mandell and Samborsky, 2008). Variations in materials include different fibre reinforced composites (using glass and carbon fibres and combinations), different laminate fabrication processes, material forms, orientations, polyester epoxy and other resins, fibre contents, and structural details. Additional characterizations are planned for thermoplastics, thick adhesives, and thick core materials.

Fibreglass has been the primary reinforcement for wind turbine composite blades. Carbon fibre has tremendous potential for use in large blades in areas where loads are acute. As research is showing, carbon fibre also has an advantage when incorporated into passive load control concepts whereby carbon fibres are placed strategically to provide enhanced bend-twist coupling, which will help shed turbulent loads (Lobitz and Veers, 2003). The extent of future use of carbon fibre is uncertain, however, because of supply and cost concerns. Some companies use carbon selectively, whereas other companies do not see enough of a performance benefit relative to the incremental cost to add it to their designs.

7.7.4.6 Atmospheric science

Accurate, reliable wind measurements and computations across scales ranging from microns to thousands of kilometres (Schreck *et al*., 2008) can improve the understanding of the wind turbine operating environment. Though the physics are strongly coupled, the problem can be subdivided into four spatio-temporal levels to facilitate explanation: 1) external design wind conditions for individual wind turbine dynamics, 2) wind project siting and array effects (wind resources and wake effects on design wind conditions), 3) mesoscale atmospheric processes, and 4) global and local climate effects. External design wind conditions affecting the individual wind turbine dynamics encompass detailed characterizations of turbine flow fields including turbulence structures needed to achieve aerodynamics load predictions accurate enough for machine designs. This area is addressed using an incremental approach involving hierarchical computational modelling (Araya *et al.,* 2006) and detailed measurements, e.g. wind tunnel and field experiments (Simms *et al*., 2001), wherein the isolated turbine is considered initially, and then inflow including the wake trailed from an upwind turbine is undertaken. Wind project siting and array effects focus on improved wake models (Thomsen and Sørensen, 1999; Frandsen *et al*., 2007) for more reliably predicting energy capture underperformance and exacerbated fatigue loading in large, multiple-row wind projects. Planetary boundary layer research is important for accurate determination of wind inflow structure and turbulence statistics in the presence of various atmospheric stability effects and complex land surface characteristics. Work in mesoscale atmospheric processes aims at improved fundamental understanding of mesoscale and local flows (Banta *et al*., 2003; Kelley *et al.,* 2004) and developing enhanced wind forecasting methods optimally suited for wind energy production forecasts and wind energy resource assessments. Modelling approaches for resolving spatial scales in the 100-m to 1000-m range, a notable gap in current capabilities (Wyngaard, 2004), could occupy a central role in future research. In global and local climate effects, work is needed to identify and understand historic trends in wind resource variability to increase confidence for future planning and validation. Similar research is needed to better predict future changes in the mean and variability of wind climate and resources (Pryor *et al.,* 2005). Also important are characterizations of large wind project influences on local/regional/global climates.

To make additional progress in many of the above areas will require interdisciplinary work to exploit previously untapped synergies. Also crucial is the need to apply experiments and observations in a coordinated fashion with computation and theory. The models that are developed as a result of this work are essential for improving 1) wind turbine design resulting from turbulent inflow, 2) wind project performance estimates, 3) wind resource mapping that identifies likely locations for projects, 4) short-term forecasting that efficiently integrates wind generation into electric systems, and 5) estimates of the impact of large-scale wind technology deployment on the local climate, as well as the impact of potential climate change effects on wind resources.

7.8 Cost trends[19]

The cost of wind energy has declined significantly since the beginnings of the modern wind industry in the 1980s and, in some circumstances, the cost of wind energy is cost-competitive with fossil generation (e.g., Berry, 2009; IEA, 2009b). Continued technology advancements in on- and off-shore wind are expected (Sections 7.7), which will support further cost reductions. Because the degree to which wind energy is utilized globally and regionally will depend largely on the economic performance of wind compared to alternative power sources, this section describes the factors that affect the cost of wind energy (7.8.1), highlights historical trends in wind project cost and performance (7.8.2), summarizes data and estimates the levelized cost of energy from wind in 2008 (7.8.3), and forecasts the potential for further cost reductions into the future (7.8.4).

7.8.1 Factors that affect the cost of wind energy

The cost of wind energy is affected by four fundamental factors: annual energy production, installation costs, operating costs, and financing costs / project operating life [TSU: unclear]. These factors affect both on-shore and off-shore wind projects, but differently. Available policy incentives can also influence the cost of wind energy, as well as the cost of other generation options, but these factors are not addressed here.

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[19] All cost data are presented in real, 2005 U.S. dollars (US2005$)

The quality of the wind resource at a given site largely determines the annual energy production from a prospective wind project, and is among the most important economic factors. Precise micro-siting of wind projects and even individual turbines is critical for maximizing energy production. The trend toward turbines with larger rotor diameters and taller towers has led to increases in annual energy production, and has also allowed wind projects in lower resource areas to become more economically competitive over time. Off-shore wind projects will, generally, be exposed to a higher wind resource than will on-shore projects.

Wind projects are capital intensive and, over the life of a project, the initial capital investment ranges from 75-80% of total expenditure, with operating costs contributing the balance (Blanco, 2009; EWEA, 2009). The capital cost of wind project installation includes the cost of the turbines (turbines, transportation to site, and installation), grid connection (cables, sub-station, interconnection), civil works (foundations, roads, buildings), and other costs (engineering, licensing, permitting, environmental assessments, and monitoring equipment). Table 7.5 shows a rough breakdown of capital cost components for modern, utility-scale wind energy projects, with the turbines comprising more than 70% of installed costs for on-shore wind projects. The remaining costs are highly site-specific. Off-shore projects are dominated by these other costs, with the turbines often contributing less than 50% of the total. Site-dependent characteristics such as water depth and distance to shore significantly affect grid connection, civil works, and other costs. Off-shore turbine foundations and internal electric grids are also considerably more costly than for on-shore projects (see also, Junginger *et al.*, 2004).

Table 7.5. Installed cost distribution for on-shore and off-shore wind projects (Blanco, 2009; EWEA, 2009)

Cost Component	**On-shore**	**Off-shore***
Turbine	71% - 76%	37% - 49%
Grid connection	10% - 12%	21% - 23%
Civil works	7% - 9%	21% - 25%
Other capital costs	5% - 8%	9% - 15%

* Off-shore cost categories consolidated from original

The operation and maintenance [TSU: please use abbr. O&M] costs of wind projects include fixed costs such as land leases, insurance, taxes, management, and forecasting services, as well as variable costs related to the maintenance and repair of turbines, including spare parts. Operation and maintenance [TSU: please use abbr. O&M] costs comprise approximately 20% of total wind project expenditure (Blanco, 2009), with roughly 50% of total operation and maintenance [TSU: please use abbr. O&M] costs associated directly with maintenance, repair, and spare parts (EWEA, 2009). Off-shore project operation and maintenance [TSU: please use abbr. O&M] costs are higher than on-shore costs due to harsher weather conditions that impede access, as well as the higher transportation costs incurred to access off-shore turbines (Blanco, 2009).

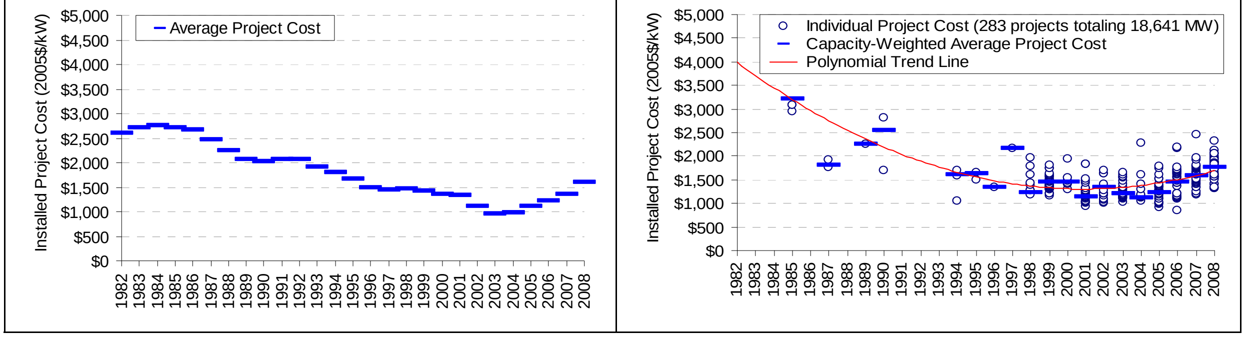
Financing arrangements, including the cost of debt and equity and the proportional use of each, can also influence the cost of wind energy, as can the expected operating life of the project. For example, ownership and financing structures have evolved in the U.S. that minimize the cost of capital while taking advantage of available tax incentives (Bolinger *et al.*, 2009a). Other research has found that the stability of policy measures supporting wind can also have a sizable impact on financing costs, and therefore the ultimate cost of wind (Wiser and Pickle, 1998; Dinica, 2006; Dunlop, 2006; Agnolucci, 2007). Because off-shore projects are still relatively new, with greater performance risk, higher financing costs are experienced than for on-shore projects (Dunlop, 2006; Blanco, 2009), and larger firms tend to dominate off-shore wind development and ownership (Markard and Petersen, 2009).

7.8.2 Historical trends

7.8.2.1 Installed capital costs

From the beginnings of commercial wind deployment to roughly 2004, the installed capital cost of on-shore wind projects dropped, while turbine size grew significantly. With each generation of wind turbine technology during this period, design improvements and turbine scaling led to decreased installed costs.

Historical installed capital cost data from Denmark and the United States demonstrate this trend (Figure 7.22(a,b). From 2004 to 2008, however, capital costs increased. Wind project costs in Denmark and the U.S. in 2008 averaged $1,600/kW and $1,800/kW, respectively, up by approximately 50% from the earlier low. Some of the reasons behind these increased costs are described in Section 7.8.3.



(a) Wind project costs in Denmark (James-Smith and Bang, 2010)

(b) Wind project costs in the United States (Wiser and Bolinger, 2009)

Figure 7.22. Installed cost of wind energy projects in (a) Denmark and (b) the United States

The installed costs of off-shore wind projects are highly site-specific, but have historically been 50% to more than 100% more expensive than on-shore projects (IEA, 2008; EWEA, 2009). Due to the small sample size and short historical record, a trend toward reduced costs over time is not clearly discernable. Off-shore wind project costs have also been influenced by the same factors that caused rising on-shore costs from 2004 through 2008, as described in Section 7.8.3.

7.8.2.2 Project performance

Wind project performance is primarily governed by local wind conditions, but is also impacted by wind turbine design optimization, performance, and availability, and by the effectiveness of operation and maintenance [TSU: please use abbr. O&M] procedures. Improved resource assessment and siting methodologies developed in the 1970s and 1980s played a major role in improved wind project productivity. Advancements in wind technology, including taller towers and larger rotors, have also contributed to increased energy capture (EWEA, 2009).

Data on capacity factors[20] achieved in 2008 for a large sample of on-shore wind projects in the U.S. show a trend toward higher capacity factors for projects built more recently, although variation in

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[20] A wind project's capacity factor is only a partial indicator of wind project performance (EWEA, 2009). Most turbine manufacturers supply variations on a given drive-train platform with multiple rotor diameters and hub heights. In general, for a given drive-train platform, increasing the hub height, the rotor diameter, or the average wind speed will result in increased capacity factor. When comparing different drive-train platforms, however, it is possible to increase annual energy capture by using a larger generator, while at the same time decreasing the wind project's capacity factor.

performance among projects built in a single year can be quite large (Figure 7.23). Higher hub heights and larger rotor sizes are primarily responsible for these improvements in energy capture, as the more recent projects in this time period were sited in increasingly lower wind resource regimes.

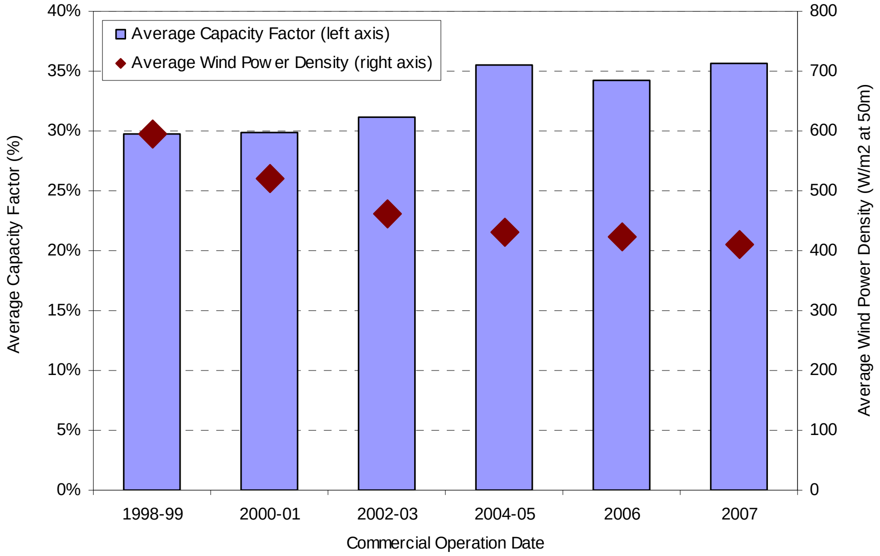


Figure 7.23. Wind project capacity factors in the U.S. (Wiser *et al.*, 2010)

Using a different (and arguably more appropriate) metric for wind project performance, annual energy production per square meter of swept rotor area (kWh/m^2) for a given wind resource site, improvements of 2-3% per year over the last 15 years have been documented (IEA, 2008; EWEA, 2009). Data from the U.S. also suggest some improvement in this metric from 1998 through 2007, though not at the 2-3% per year level (Wiser *et al.*, 2010).

7.8.2.3 Operation and maintenance

Modern turbines that meet IEC standards are designed for a 20-year life, and project lifetimes may even exceed 20 years if O&M costs remain at an acceptable level. However, few wind projects were constructed 20 or more years ago, and therefore there is limited experience in project operations over this entire time period. Moreover, those projects that have reached or exceeded their 20-year lifetime tend to have turbines that are much smaller and less sophisticated than their modern counterparts. Early turbines were also designed using more conservative criteria, though they followed less stringent standards than today's designs. As a result, these early projects only offer limited guidance for estimating operation and maintenance [TSU: please delete] (O&M) costs for more-recent turbine designs.

In general, operation and maintenance [TSU: please use abbr. O&M] costs during the first couple [TSU: of] years of a project's life are covered, in part, by manufacturer warranties that are included in the turbine purchase, resulting in lower ongoing costs than in subsequent years. Newer turbine models also tend to have lower initial operating costs than older models, with maintenance costs increasing as projects age (Blanco, 2009; EWEA, 2009; Wiser and Bolinger, 2009). New technologies, such as condition monitoring equipment, could lead to lower O&M costs over the life of a project than might otherwise occur. Off-shore wind projects have historically incurred higher operation and maintenance [TSU: please use abbr. O&M] costs than on-shore projects (Junginger *et al.*, 2004; EWEA, 2009; Lemming *et al.*, 2009).

7.8.3 Current conditions

7.8.3.1 Installed capital costs

The cost for most on-shore wind projects in Europe ranged from roughly $1,500/kW to $2,000/kW in 2008 (Milborrow, 2009), while projects installed in the United States in 2008 averaged $1,750/kW (Wiser and Bolinger, 2009). Costs in certain developing markets are somewhat lower: for example, average wind project costs in China in 2008 were around $1,100/kW in real 2005$, driven in part by the dominance of several Chinese turbine manufacturers serving the market with low-installed-cost wind turbines (Li and Ma, 2009).

Overall, wind project costs rose from 2004 to 2008 (Figure 7.22), an increase primarily caused by the rising price of wind turbines (Bolinger and Wiser, 2009), which has been attributed to a number of factors, including: escalation (in real terms) in the cost of labour and materials inputs; increasing profit margins among turbine manufacturers and their component suppliers; the relative strength of the Euro currency; and the increased size of turbine rotors and hub heights (Bolinger *et al.,* 2009b). Increased rotor diameters and hub heights have enhanced the energy capture of modern wind turbines, but those performance improvements have come with increased installed turbine costs, measured on a $/kW basis. The costs of raw materials, including steel, copper, cement, aluminum, and carbon fibre, also rose sharply from 2004 through mid-2008 as a result of strong global economic growth. In addition to higher raw materials costs, the strong demand for wind turbines over this period put upward pressure on labour costs, and enabled turbine manufacturers and their component suppliers to boost profit margins. Strong demand, in excess of available supply, also placed particular pressure on critical components such as gearboxes and bearings (Blanco, 2009), which have traditionally been provided by only a small number of suppliers. Moreover, because many of the global wind turbine manufacturers have historically been based in Europe, and many of the critical components like gearboxes and bearings have similarly been manufactured in Europe, the relative value of the Euro to other currencies such as the U.S. dollar also contributed to wind price increases in certain countries (Bolinger *et al.,* 2009b).

Turbine manufacturers and component suppliers responded to the tight supply by expanding or adding new manufacturing facilities. Coupled with somewhat weakened demand for wind turbines and reductions in materials costs that began in late 2008 as a result of the global financial crisis, these trends began to moderate wind turbine costs at the beginning of 2009. Wind turbine cost reductions of as much as 25% were reported by mid-2009, relative to the mid-2008 high point (Wiser and Bolinger, 2009).

Due to the relatively small number of off-shore wind installations, cost data are sparse. Off-shore wind project costs are considerably higher than those for on-shore projects, and the factors that have increased the cost of on-shore projects have similarly affected the off-shore sector. The limited availability of turbine manufacturers supplying the off-shore market, and of vessels to install such projects, has exacerbated cost increases. Off-shore wind projects over 50 MW, either built between 2006 and 2008 or planned for 2009-10, have installed costs that range approximately $2,000/kW to $5,000/kW (IEA, 2008; IEA, 2009b; Milborrow, 2009; Snyder and Kaiser, 2009), with most estimates in a narrower range of $3,200/kW to $4,600/kW (Milborrow, 2009).

7.8.3.2 Project performance

On-shore wind project performance varies significantly even within an individual country, primarily as a function of the wind resource, with capacity factors ranging from below 20% to more than 50% depending on the local resource conditions. Among countries, variations in average project performance again reflect differing wind resource conditions: the average capacity factor for Germany's installed wind projects has been estimated at 20.5% (BTM, 2009); European country-level average capacity factors range from 20-30% (Boccard, 2009); and the average capacity factor for U.S. wind projects is nearly 34% (Wiser and Bolinger, 2009). Off-shore wind projects often experience a narrower range in capacity factors, with a typical range of 35% to 45% for the European projects installed to date (Lemming *et al.*, 2009).

Because of these variations among countries and individual projects, which are primarily driven by local wind energy resource conditions, estimates of the levelized cost of wind energy must include a range of energy production estimates. Moreover, because the attractiveness of off-shore projects is enhanced by the potential for greater energy production than for on-shore projects, performance variations among on- and off-shore projects must also be considered.

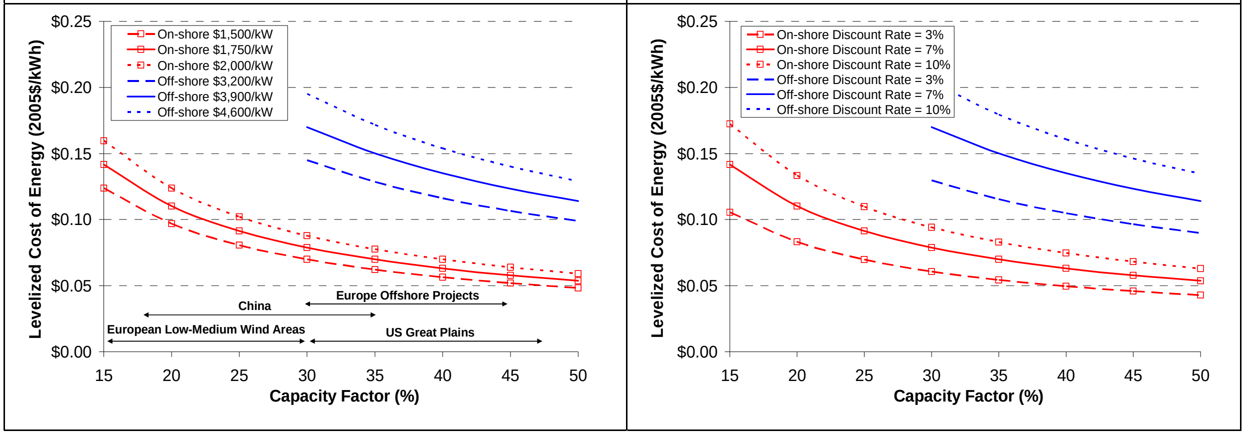
7.8.3.3 Operation and maintenance

Though fixed operation and maintenance [TSU: please use abbr. O&M] costs, such as insurance, land payments and routine maintenance are relatively easy to estimate, variable costs such as repairs and spare parts are more difficult to predict (Blanco, 2009). operation and maintenance [TSU: please use abbr. O&M] costs vary by project, region, project age and the availability of a local serving infrastructure, among other factors. Levelized on-shore wind operation and maintenance [TSU: please use abbr. O&M]costs are often estimated to range from $0.012/kWh to $0.023/kWh (Blanco, 2009): these figures are reasonably consistent with costs reported in IEA (2008), EWEA (2009), and Wiser and Bolinger (2009), and represent a relatively small fraction of the total delivered cost of wind energy.

Limited empirical data exist on operations costs for off-shore projects, due in large measure to the limited number of operating projects and the limited duration of those projects' operation. Reported or estimated O&M costs that are available for off-shore projects installed since 2002 range from $0.02/kWh to $0.04/kWh (EWEA, 2009; IEA, 2009b; Lemming *et al.*, 2009; Milborrow, 2009).

7.8.3.4 Levelized cost of energy estimates

Using the methods summarized in Chapter 1, the levelized cost of wind energy for projects built in 2008 is presented in Figure 7.24(a, b). Estimated costs are presented over a range of energy production estimates to represent the cost variation associated with inherent differences in the wind resource. The x-axis for these charts roughly correlates to annual average wind speeds from 6 m/s to 10 m/s. On-shore capital costs are assumed to range from $1,500/kW to $2,000/kW (mid-point of $1,750/kW); installed costs for off-shore projects range from $3,200/kW to $4,600/kW (mid-point of $3,900/kW). Levelized operation and maintenance [TSU: please use abbr. O&M] costs are assumed to average $0.016/kWh and $0.03/kWh over the life of the project for on-shore and off-shore projects, respectively. A project design life of 20 years is assumed, and discount rates of 3% to 10% (mid-point estimate of 7%) are used to produce levelized cost estimates. Taxes and policy incentives are not included in the levelized cost of energy calculations.



(a) Cost of wind energy as a function of project performance and capital cost*

(b) Cost of wind energy as a function of project performance and discount rate**

* Discount rate assumed to equal 7%

** On-shore capital cost assumed at $1,750/kW, and off-shore at $3,900/KW

Figure 7.24. Estimated levelized cost of on-shore and off-shore wind energy, 2008

The levelized cost of on- and off-shore wind energy in 2008 varies substantially, depending on assumed capital costs, energy production estimates, and discount rates. For on-shore wind, levelized costs can exceed $0.10/kWh in lower resource areas, and be as low as around $0.05/kWh in the highest wind resource regimes. Off-shore wind is generally more expensive than on-shore wind, with levelized costs that can range from $0.10/kWh to $0.20/kWh.

7.8.4 Potential for further reductions in the cost of wind energy

The modern wind industry has developed over a period of 30 years. Though the dramatic cost reductions seen in the past decades will not continue indefinitely, the potential for further reductions remain given the many potential areas of technological advance described in Section 7.7. This potential spans both on- and off-shore wind energy applications; however, given the relative immaturity of off-shore wind technology, greater cost reductions can be expected in that segment.

Two approaches are commonly used to forecast the future cost of wind energy: (1) learning curve estimates that assume that future wind costs will follow a trajectory that is similar to an historical learning curve based on past costs; and (2) engineering-based estimates of the specific cost reduction possibilities associated with new or improved wind technologies or manufacturing capabilities.

7.8.4.1 Learning curve estimates

Learning curves have been used extensively to understand past cost trends and to forecast future cost reductions for a variety of energy technologies (e.g., McDonald and Schrattenholzer, 2001; Kahouli-Brahmi, 2009). Learning curves start with the premise that increases in the cumulative capacity of a given technology lead to a reduction in its costs. The principal parameter calculated by learning curve studies is the learning rate: for every doubling of cumulative installation or production, the learning rate specifies the associated percentage reduction in costs.

A number of studies have evaluated learning rates for on-shore wind energy (Table 7.6). There is a wide range of calculated learning rates, from 4% to 32%. This wide variation can be explained by differences in learning model specification (e.g., one factor or multi-factor learning curves), variable selection and assumed system boundaries (e.g., whether installed cost, turbine cost, or levelized energy costs are explained, and whether global or country-level cumulative installations are used), data quality, and the time period over which data are available. Because of these differences, the various learning rates for wind presented in Table 7.6 cannot easily be compared.

Table 7.6. Summary of learning curve literature for wind energy

		Global or National		
Authors	**Learning By Doing Rate (%)**	**Independent Variable (cumulative installed capacity)**	**Dependent Variable**	**Data Years**
Neij 1997	4%	Denmark	Denmark (turbine cost)	1982-1995
Mackay and Probert 1998	14%	USA	US (turbine cost)	1981-1996
Neij 1999	8%	Denmark	Denmark (turbine cost)	1982-1997
Wene 2000	32%	USA **	USA (production cost)	1985-1994
Wene 2000	18%	European Union **	European Union (production cost)	1980-1995
Miketa and Schrattenholzer 2004 *	10%	Global	global (installed cost)	1971-1997
Junginger et al. 2005	19%	Global	UK (installed cost)	1992-2001
Junginger et al. 2005	15%	Global	Spain (installed cost)	1990-2001
Klaassen et al. 2005 *	5%	Germany, Denmark, and UK	Germany, Denmark, and UK (installed cost)	1986-2000
Kobos et al. 2006 *	14%	Global	global (installed cost)	1981-1997
Taylor et al. 2006	23%	Global	California (installed cost)	not reported
Jamasb 2007 *	13%	Global	global (installed cost)	1980-1998
Söderholm and Sundqvist 2007	5%	Germany, Denmark, and UK	Germany, Denmark, and UK (installed cost)	1986-2000
Söderholm and Sundqvist 2007 *	4%	Germany, Denmark, and UK	Germany, Denmark, and UK (installed cost)	1986-2000
Neij 2008	17%	Denmark	Denmark (production cost)	1980-2000
Kahouli-Brahmi 2009	17%	Global	global (installed cost)	1979-1997
Kahouli-Brahmi 2009 *	27%	Global	global (installed cost)	1979-1997
Nemet 2009	11%	Global	California (turbine cost)	1981-2004

* Indicates a two-factor learning curve that also includes R&D; all others are one-factor learning curves

** Independent variable is cumulative production of electricity

There are also a number of limitations in the use of such models to forecast future costs. First, learning curves model how costs have decreased with increased production in the past, but do not explain the reasons behind the decrease. If learning curves are used to forecast future cost trends, one must assume that the factors that have driven costs in the past will be sustained into the future. In reality, as technologies mature, diminishing returns in cost reduction can be expected (Arrow, 1962; Ferioli *et al.*, 2009). Second, the most appropriate cost measure for wind is arguably the levelized cost of energy, as wind energy production costs are affected by both installed costs and energy production (EWEA, 2009; Feroli *et al.*, 2009). Unfortunately, only two of the published studies calculate the learning rate for wind using a levelized cost of energy metric (Wene, 2000; Neij, 2008); most studies have used the more-readily available metrics of total installed cost or turbine cost. Third, a number of the published studies have sought to explain cost trends based on cumulative wind installations or production in individual countries or regions; because the wind industry is global in scope, however, it is likely that most learning is occurring based on cumulative global installations. Finally, from 2004 through 2008, the installed cost of wind projects increased substantially, countering the effects of learning, and questioning the sole reliance on cumulative installations as a predictor of future costs.

7.8.4.2 Engineering model estimates

Whereas learning curves examine aggregate historical data to forecast future trends, engineering-based models focus on the possible cost reductions associated with specific design changes and/or technical advancements. These models can lend support to learning curve predictions by defining the technology advances that can yield cost reductions and energy production increases.

These models have been used to estimate the impact of potential technology improvements on wind project capital costs and energy production, as highlighted earlier in Section 7.3 (based on U.S. DOE, 2008). Given these possible technology advancements, the U.S. DOE (2008) estimates that installed on-shore wind costs may decline by 10% by 2030, while energy production may increase by roughly 15%. Combined, these two impacts correspond to a reduction in the levelized cost of energy from on-shore wind of 17% by 2030.

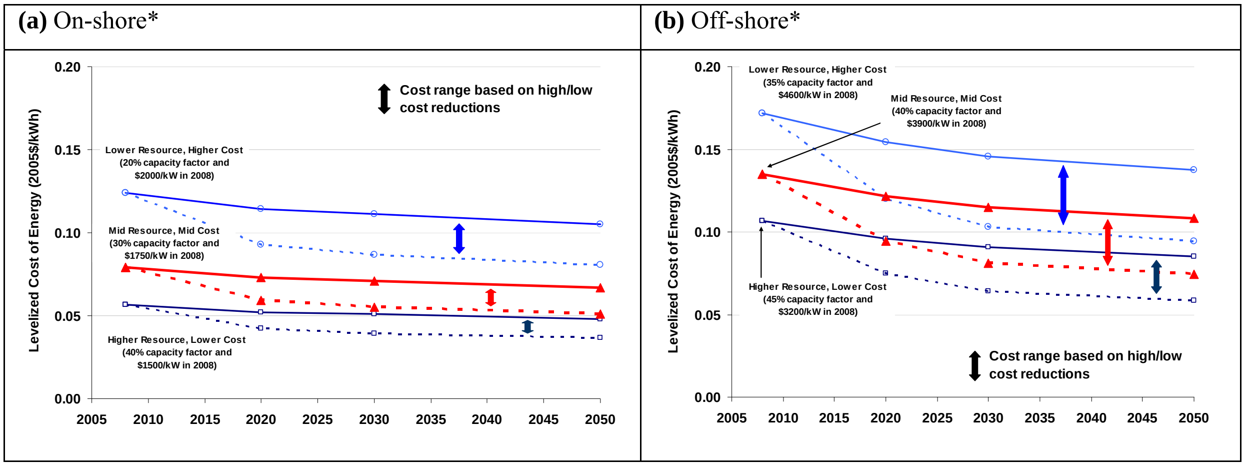
Given the relative immaturity of off-shore wind technology, there is arguably greater potential for technical advancements in off-shore wind than in on-shore wind, particularly in foundation design, installation, electrical system design, and operation and maintenance [TSU: please use abbr. O&M] costs. Future energy cost reductions have been estimated by associating potential cost reductions with these technical improvements, resulting in cost reduction estimates ranging from 18-39% by 2020, and 17-66% by 2030 (Junginger *et al.*, 2004; Carbon Trust, 2008a; Lemming *et al.*, 2009).

7.8.4.3 Projected levelized cost of wind energy

A number of studies have estimated the cost trajectory for on-shore and off-shore wind based on learning curve estimates and/or engineering models (Junginger *et al.*, 2004; Carbon Trust, 2008a; GWEC 2008; IEA, 2008; Neij, 2008; U.S. DOE, 2008; Lemming *et al.*, 2009).

Using the estimates and assumptions for the percentage cost reduction expected from these studies, a range of levelized cost trajectories have been developed for representative future on-shore and off-shore wind projects (Figure 7.25(a, b)). In each of the graphics, a high, low, and mid-level starting point for the levelized cost of energy is calculated using various combinations of project-level capacity factor and installed cost assumptions, representing a reasonable range of 2008 values. These levelized cost estimates for 2008 are the same as presented earlier in Figure 7.24.

To forecast a range of future costs, high and low levelized cost reduction estimates were developed based on the literature cited above. That literature suggested a range of levelized cost reductions for on-shore wind of 7.5-25% by 2020 and 15-35% by 2050, and for off-shore wind of 10-30% by 2020 and 20-45% by 2050.


(a) On-shore*

(b) Off-shore*

Starting-point O&M costs are assumed to equal $0.016/kWh (on-shore) and $0.03.kWh (off-shore); a 7% discount rates is used throughout

Figure 7.25. Projected levelized cost of (a) on-shore and (b) off-shore wind energy, 2008-2050

Based on these assumptions, the levelized cost of on-shore wind could range from roughly $0.04-0.11/kWh in 2050, depending on the wind resource, installed project costs, and the speed of cost reduction. Off-shore wind is likely to experience somewhat deeper cost reductions, with a range of expected levelized costs of $0.06-0.14/kWh in 2050.

Significant uncertainty exists over future wind technology costs, and the range of costs associated with varied wind resource strength introduces even greater uncertainty. As installed wind capacity levels increase, higher quality resource sites will tend to be utilized first, leaving higher-cost sites for later deployment. As a result, the average levelized cost of wind will depend on the amount of deployment. This “supply-curve” affect is not captured in the estimates presented in Figure 7.26: those projections present potential cost reductions associated with wind projects located in specific wind resource regimes. The estimates presented here therefore provide an indication of the technology advancement potential for on- and off-shore wind, but should be used with caution.

7.9 Potential deployment

Wind energy offers significant potential for near- and long-term carbon emissions reduction. The wind energy capacity installed by the end of 2008 delivers roughly 1.5% of worldwide electricity supply, and global wind electricity supply could grow to in excess of 20% by 2050. On a global basis, the wind resource is unlikely to constrain further development (Section 7.2). On-shore wind is a mature technology that is already being deployed at a rapid pace (see Sections 7.3 and 7.4), therefore offering an immediate option for reducing carbon emissions in the electricity sector. In good wind resource regimes, the cost of wind can be competitive with other forms of electricity generation (especially where environmental impacts are monetized: see Section 7.8), and no fundamental technical barriers exist that preclude increased levels of wind penetration into electricity supply systems (see Section 7.5). Continued technology advancements and cost reductions in on- and off-shore wind are expected (see Sections 7.7 and 7.8), which will further improve the carbon emissions mitigation potential of wind energy over the long term.

This section begins by highlighting near-term forecasts for wind energy deployment (7.9.1). It then discusses the prospects for and barriers to wind energy deployment in the longer-term and the potential role of that deployment in meeting various GHG mitigation targets (7.9.2). Both subsections are largely based on energy-market forecasts and carbon and energy scenarios literature published in the 2007-2009 time period.

7.9.1 Near-term forecasts

The rapid increase in global wind capacity from 2000-2008 is expected by many studies to continue in the near- to medium-term (Table 7.7). From the roughly 120 GW of wind capacity installed at the end of 2008, the IEA (IEA, 2009a) and U.S. Energy Information Administration (U.S. EIA, 2009) reference-case forecasts predict growth to 295 GW and 249 GW by 2015, respectively. Wind industry organizations predict even faster deployment rates, noting that past IEA and EIA forecasts have understated actual wind growth by a sizable margin (BTM, 2009; GWEC, 2009). However, even these more-aggressive forecasts estimate that wind energy will contribute less than 4% of global electricity supply by 2015. Asia, North America, and Europe are projected to lead in wind additions over this period.

Table 7.7. Near-Term Global Wind Energy Forecasts

Study	**Wind Energy Forecast**		
	Installed Capacity	**Year**	**% of Global Electricity Supply**
IEA(2009a)	295 GW	2015	2.8%
U.S. EIA (2009)	249 GW	2015	2.2%
GWEC (2009)	332 GW	2013	not available
BTM (2009)	343 GW	2013	3.4%

7.9.2 Long-term deployment in the context of carbon mitigation

A number of studies have tried to assess the longer-term potential of wind energy, especially in the context of carbon mitigation scenarios. As a variable, location-dependent resource with limited dispatchibility, modelling the economics of wind energy expansion presents unique challenges (U.S. DOE, 2008; Neuhoff *et al.*, 2008). The resulting differences among studies of the long-term deployment of wind may therefore reflect not just varying input assumptions and assumed policy and institutional contexts, but also differing modelling or scenario analysis approaches.

The IPCC's Fourth Assessment Report assumed that on- and off-shore wind could contribute 7% of global electricity supply by 2030, or 2,200 TWh/yr (~ 8 EJ) (IPCC, 2007). This figure is higher than some commonly cited business-as-usual, reference-case forecasts, since the IPCC estimate is not a business-as-usual case. The IEA's World Energy Outlook reference-case, for example, predicts 1,535 TWh/yr of wind by 2030, or 4.5% of global electricity supply (IEA, 2009a). The U.S. EIA forecasts 1,214 TWh/yr of wind energy in its 2030 reference case projection, or 3.8% of net electricity production from central producers (U.S. EIA, 2009).

A summary of the literature on the possible contribution of RE supplies in meeting global energy needs under a range of CO_2 stabilization scenarios is provided [TSU: in/by] Chapter 10. Focusing specifically [TSU: on] wind energy, Figure 7.26 and Figure 7.27 present modelling results on the global supply of wind energy (in EJ and as a percent of global electricity demand, respectively); refer to Chapter 10 for a full description of this literature. Wind energy deployment results for 2020, 2030, and 2050 are presented for three CO_2 stabilization ranges, based on the IPCC's Fourth Assessment Report: 600-1000 ppm-CO_2 (reference cases), 440-600 ppm (Categories III and IV), and 300-440 ppm (Categories I and II).

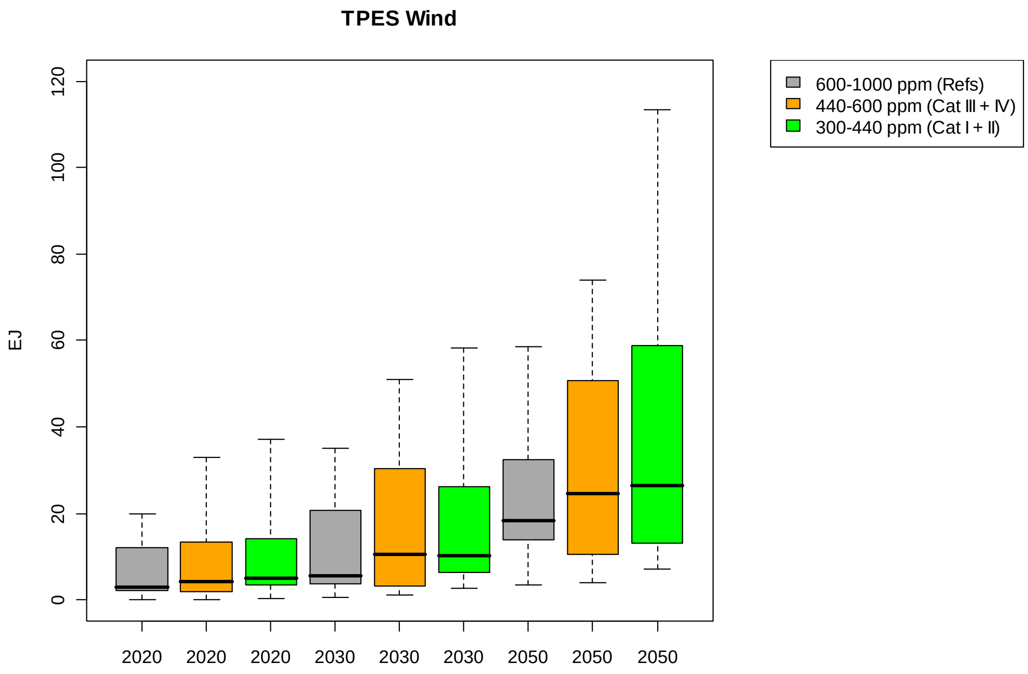


Figure 7.26. Global supply of wind energy in carbon stabilization scenarios (median, 25th to 75th percentile range, and absolute range)

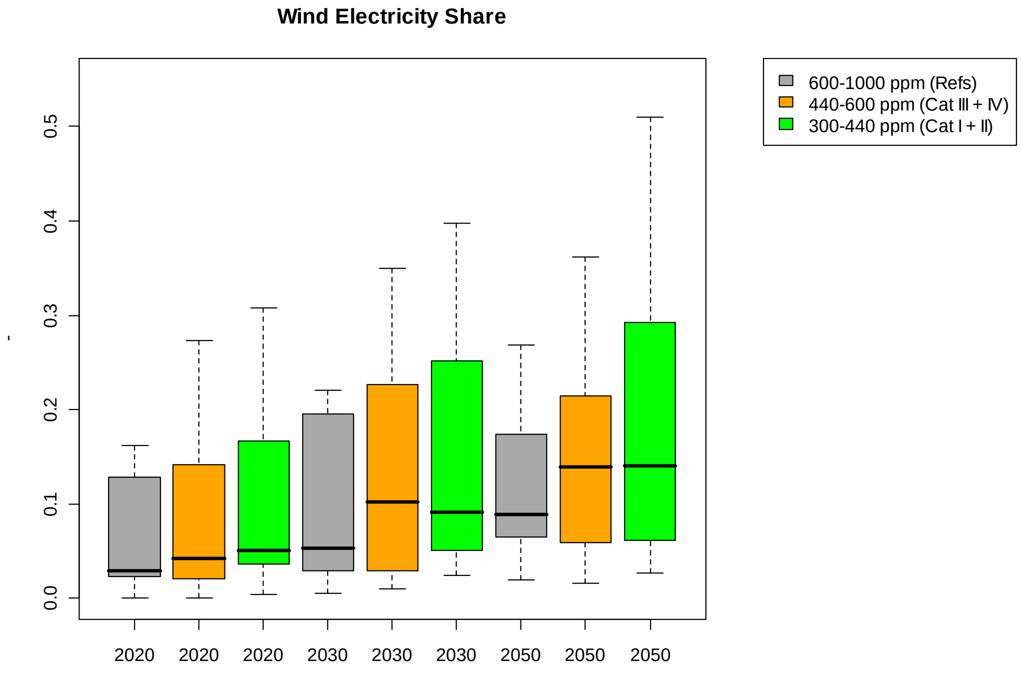


Figure 7.27. Wind electricity share in total global electricity supply (median, 25th to 75th percentile range, and absolute range)

The reference-case projections of wind energy's role in global energy supply span a broad range, but with a median of roughly 3 EJ in 2020, 6 EJ in 2030, and 18 EJ in 2050 (Figure 7.9.1). Substantial growth of wind energy is therefore projected to occur even in the absence of GHG mitigation policies, with wind energy's median contribution to global electricity supply rising from 1.5% in 2008 to 8.9% in 2050 (Figure 7.9.2). The contribution of wind energy grows as GHG mitigation policies are assumed to become more stringent: by 2030, wind energy's median contribution equals roughly 10 EJ (~10% of global electricity supply) in the 440-600 and 300-400 ppm-CO_2 stabilization ranges, increasing to 25-27 EJ by 2050 (~14% of global electricity supply).[21]

The diversity of approaches and assumptions used to generate these scenarios is great, however, resulting in a wide range of findings. Reference case results for global wind energy supply in 2050 range from 3-58 EJ (median of 18 EJ), or 2-27% (median of 9%) of global electricity supply. In the most-stringent 300-440 ppm stabilization scenarios, wind energy supply in 2050 ranges from 7-113 EJ (median of 27 EJ), equivalent to 3-51% (median of 14%) of global electricity supply.

Despite this wide range, the IPCC (2007) estimate for potential wind energy supply of roughly 8 EJ by 2030 (which was largely based on literature available through 2005) appears somewhat conservative compared to the more-recent scenarios literature presented above. Other updated forecasts of the possible role of wind energy in meeting global energy demands confirms this assessment, as the IPCC (2007) estimate is roughly one-third to one-half that shown in GWEC/GPI (2008) and Lemming *et al.* (2009). The IPCC (2007) estimate is more consistent with but still somewhat lower than that offered by the IEA World Energy Outlook (2009; 450 ppm case).

Though the literature summarized in Figures 7.9.1 and 7.9.2 shows an increase in wind energy supply with increasingly aggressive GHG targets, that impact is not as great as it is for biomass, geothermal, and solar energy, where increasingly stringent carbon stabilization ranges lead to more-dramatic increases in technology deployment (see Chapter 10). One explanation for this result is that wind energy is already relatively mature and economically competitive; as a result, deployment is predicted to proceed rapidly even in the absence of aggressive efforts to reduce carbon emissions.

The scenarios literature also shows that wind energy could play a significant long-term role in reducing global carbon emissions: by 2050, the median contribution of wind energy in the two carbon stabilization scenarios is around 25 EJ, increasing to 50 EJ at the 75th percentile, and to more than 100 EJ in the highest scenario. To achieve this contribution requires wind energy to deliver around 14% of global electricity supply in the median case, or 25% at the 75th percentile. Other scenarios generated by wind and RE organizations are consistent with this median to 75th percentile range; GWEC/GPI (2008) and Lemming *et al.* (2009), for example, estimate the possibility of 32-37 EJ of wind energy supply by 2050.

Even the highest estimates for long-term wind energy production in Figure 7.9.1 are within the global resource estimates presented in Section 7.2, and while efforts may be required to ensure an adequate supply of labour and materials, no fundamental long-term constraints to materials supply, labour availability, or manufacturing capacity are envisioned if policy frameworks for wind energy are sufficiently attractive (e.g., U.S. DOE, 2008). To enable the necessary investment over the long

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[21] In addition to the global scenarios literature, a growing body of work has sought to understand the technical and economic limits of wind deployment in regional electricity systems. These studies have sometimes evaluated higher levels of deployment than contemplated by the global scenarios, and have often used more-sophisticated modelling tools. For a summary of a subset of these scenarios, see Martinot *et al*., 2007; examples of studies of this type include dena, 2005 (Germany); EC, 2006 (Europe); Nikolaev *et al*., 2008, 2009 (Russia); and U.S. DOE, 2008 (United States).[21] In general, these studies confirm the basic findings from the global scenarios literature: wind deployment to 10% of global electricity supply and then to 20% or more are plausible, assuming that cost and policy factors are favourable towards wind deployment.

term, however, economic incentive policies intended to reduce carbon emissions and/or increase renewable energy supply of adequate economic attractiveness *and* stability would likely be required (see Chapter 11). Additionally, four other challenges would likely need to be addressed to reach the levels of wind energy supply discussed in this section.

First, wind energy would need to expand beyond its historical base in Europe and, increasingly, the U.S. and China. The IEA WEO reference-case forecast projects the majority of wind deployment by 2030 to come from OECD Europe (40%), with lesser quantities from OECD North America (26%) and portions of Asia (e.g., 15% in China and 5% in India) (IEA, 2009a). Under higher-penetration scenarios, however, a greater geographic distribution of wind deployment is likely to be needed. Scenarios from GWEC/GPI (2008), EREC/GPI (2008), and IEA (2008), for example, suggest that North America, Europe, and China are most-likely to be the areas of greatest wind energy deployment, but a large number of other regions are also significant contributors to wind energy generation growth in these scenarios (Table 7.8).[22] Enabling this level of wind development in regions new to wind energy would be a challenge, and would benefit from institutional and technical knowledge transfer from those regions that are already witnessing substantial wind energy activity (e.g., Lewis, 2007; IEA, 2009b).

Table 7.8. Regional distribution of global wind energy generation (percentage of total worldwide wind generation)

Region	**GWEC/GPI (2008)*** **2030** ***Advanced***	**EREC/GPI (2008)** **2050** ***Energy Revolution***	**IEA ETP (2008)** **2050** ***BLUE***
Global Supply of Wind Energy (EJ)	20 EJ	28 EJ	19 EJ
OECD North America	22%	20%	13%
Latin America	8%	9%	10%
OECD Europe	15%	13%	23%
Transition Economies	3%	9%	3%
OECD Pacific	9%	10%	7%
China	19%	20%	31%
India	10%	7%	4%
Developing Asia	9%	7%	3%
Africa and Middle East	5%	5%	6%

* For GWED/GPI (2008), percentage of worldwide wind capacity is presented.

Second, due to resource and siting constraints, some regions would likely rely heavily on additions to off-shore wind energy, particularly Europe. Estimates of the proportion of total wind energy supply likely to be delivered from off-shore developments in 2050 range from 18-30% (EREC/GPI, 2008; IEA, 2008; Lemming *et al*., 2009), while the IEA forecasts a 20-28% share by 2030 (IEA, 2009a). Increases in off-shore wind of this magnitude would require technological advancements and cost reductions given the state of the technology. Though continued and expanded R&D is expected to lead to important cost reductions for on-shore wind energy technology, enhanced R&D

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[22] Many of these other regions have lower expected electricity demands. As a result, some of the regions with a small contribution to global wind energy generation are still projected to obtain a sizable fraction of their electricity supply from wind in these scenarios.

expenditures by government and industry may be especially important for off-shore wind energy given the less mature state of off-shore wind technology and development (see Section 7.7).

Third, technical and institutional solutions to transmission constraints and operational integration concerns will need to be implemented. Analysis results and experience suggest that power systems can operate with up to roughly 20% wind energy with relatively modest integration costs (see Section 7.5 and Chapter 8) and, while few studies have explored wind electricity supply in excess of 20% in detail, there is little evidence to suggest that an inherent technical limit exists to wind energy's contribution to electricity supply.[23] Nevertheless, concerns about operational integration and power systems reliability will grow with wind energy deployment, and efforts to ensure adequate system-wide flexibility, employ more-restrictive grid connection standards, develop and use improved wind forecasting systems, and encourage load flexibility and electrical storage are warranted. Given the locational dependence of the wind energy resource, substantial new transmission infrastructure both on- and off-shore would also be required under even the more modest wind deployment scenarios presented above. Both cost and institutional barriers would need to be overcome to develop the needed transmission infrastructure (see Section 7.6 and Chapter 8).

Finally, given concerns about the social and environmental impacts of wind projects summarized in Section 7.6, efforts to better understand the nature and magnitude of these impacts, together with efforts to mitigate any remaining concerns, will need to be pursued in concert with increasing wind energy deployment. Though community and scientific concerns need to be addressed, streamlined planning, siting, and permitting procedures for both on-shore and off-shore wind may be required to enable the capacity additions envisioned under these scenarios.

Overall, the evidence suggests that wind penetration levels that approach or exceed 10% of global electricity supply by 2030 are feasible, assuming that cost and policy factors are favourable towards wind energy deployment. The scenarios further suggest that even-more ambitious policies and/or technology improvements may allow wind production to ultimately reach or exceed 20% of global electricity supply, and that these levels of wind energy supply would be economically attractive within the context of global carbon mitigation scenarios. The degree to which wind energy is utilized in the future will largely depend on: continued economic performance [TSU: improvements] of wind energy compared to alternative power sources; national and regional policies to directly or indirectly support wind energy deployment; local siting and permitting challenges; and real or perceived concerns about the ability to integrate wind energy into electricity networks.

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[23] Some studies have looked at wind energy penetrations in excess of 20% in certain regions, often using a somewhat-less-detailed analysis procedure than formal wind energy integration studies, and often involving the use of structural change in generation portfolios, electrical or thermal storage, plug-in hybrid vehicles and the electrification of transportation, demand response, and/or other technologies to manage the variability of wind energy (e.g., Grubb, 1991; Watson *et al*., 1994; Lund and Münster, 2003; Kempton and Tomic, 2005; Lund, 2006; Black and Strbac, 2006; DeCarolis and Keith, 2006; Denholm, 2006; Cavallo, 2007; Greenblatt *et al*., 2007; Hoogwijk *et al*.. 2007; Benitez *et al.,* 2008; Lamont, 2008; Leighty, 2008; Lund and Kempton, 2008). These studies confirm that there are no insurmountable technical barriers to increased wind energy supply; instead, as deployment increases, grid expansion and operational integration costs will increase, constraining growth on economic terms. These studies also find that new technical solutions that are not otherwise required at lower levels of wind energy deployment, such an expanded use of storage and responsive loads, will also become increasingly valuable at high levels of wind energy development.

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